

## Analog experiments in volcanology: towards multimethod, upscaled and integrated models

Sam Poppe <sup>\*1,2</sup>, Johan Gilchrist<sup>3,4</sup>, Eric Christophe Pascal Breard <sup>4,5</sup>, Alison Graettinger<sup>6</sup>, Stephen Pansino<sup>7</sup>

1. Centrum Badań Kosmicznych Polskiej Akademii Nauk (CBK PAN), Bartycka 18A, 00-716 Warszawa, Warsaw, Poland
2. Laboratoire G-Time, Department of Geosciences, Environment and Society, Université libre de Bruxelles, Brussels, Belgium
3. Geological Fluid Dynamics Laboratory, Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, Canada
4. Department of Earth Sciences, University of Oregon, Eugene, OR, USA.
5. School of Geosciences, University of Edinburgh, The King's Building, Edinburgh, Scotland
6. Department of Earth and Environmental Sciences, University of Missouri Kansas City, Kansas City, MO, USA
7. Department of Earth Science, Durham University, Durham, UK

\*contact: sampoppe@cbk.waw.pl, [sam35poppe@gmail.com](mailto:sam35poppe@gmail.com)

\*\*\*\*\*  
This manuscript has been published in BULLETIN OF VOLCANOLOGY. The final version of this manuscript is available at the 'Peer-reviewed publication DOI' link on the right-hand side of this webpage.  
\*\*\*\*\*

Please refer to this work as:

Poppe, S., Gilchrist, J., Breard, E.C.P., Graettinger, A., Pansino, S. (2022). Analog experiments in volcanology: towards multimethod, upscaled and integrated models. *Bulletin of Volcanology*, 84:52. <https://doi.org/10.1007/s00445-022-01543-x>

# 1 Analog experiments in volcanology: towards multimethod, upscaled and integrated models

2  
3 Sam Poppe <sup>\*1,2</sup>, Johan Gilchrist<sup>3,4</sup>, Eric Christophe Pascal Breard <sup>4,5</sup>, Alison Graettinger<sup>6</sup>, Stephen Pansino<sup>7</sup>

4  
5 1. Centrum Badań Kosmicznych Polskiej Akademii Nauk (CBK PAN), Bartycka 18A, 00-716 Warszawa, Warsaw,  
6 Poland

7 2. Laboratoire G-Time, Department of Geosciences, Environment and Society, Université libre de Bruxelles,  
8 Brussels, Belgium

9 3. Geological Fluid Dynamics Laboratory, Department of Earth, Ocean and Atmospheric Sciences, University of  
10 British Columbia, Vancouver, Canada

11 4. Department of Earth Sciences, University of Oregon, Eugene, OR, USA.

12 5. School of Geosciences, University of Edinburgh, The King's Building, Edinburgh, Scotland

13 6. Department of Earth and Environmental Sciences, University of Missouri Kansas City, Kansas City, MO, USA

14 7. Department of Earth Science, Durham University, Durham, UK

15 \*contact: sampoppe@cbk.waw.pl, [sam35poppe@gmail.com](mailto:sam35poppe@gmail.com)

## 16 17 ABSTRACT

18 For decades scaled analog experiments have improved the understanding of a broad range of  
19 multiphase volcanological processes in controlled laboratory environments. Successfully modeled  
20 processes include magma flow through magma reservoirs, conduits and sheets, associated crustal  
21 deformation, lava flow, volcanic plume dynamics, ash cloud dispersion, pyroclast sedimentation,  
22 pyroclastic density currents and debris flows. Prior to the advent of computational modeling in  
23 volcanology, analog experiments were the primary method used to test newly developed concepts.  
24 Over the past two decades, technological advances have led to increased quantification of model  
25 observables, including deformation fields, lava flow rheologies, bubble and particle suspension  
26 compositions, runout distances, plume geometries, and rates of ash cloud spreading and  
27 sedimentation. For experimental results to yield further insights in volcanic processes and observables  
28 directly useful to volcano monitoring efforts, we expect future progress to focus on three major fronts:  
29 1) improved multimethod measurements in experiments; 2) upscaling to near-natural-scale  
30 experiments conducted by multidisciplinary teams at internationally shared facilities; and 3)  
31 integration with computational models that will guide future geophysical observations and predictions  
32 of volcanic activity. This way, analog experiments will bridge gaps between other techniques in  
33 volcanology and improve our understanding and forecasting of volcanic activity from the Earth's  
34 mantle to the surface and into the atmosphere.

## 35 36 INTRODUCTION

37 Observing magmatic and volcanic processes is limited to indirect observations of subsurface magma  
38 movements using complex geophysical methods, challenging remote sensing techniques, incomplete  
39 monitoring networks that produce incompatible data sets, and hazardous field conditions (Loughlin et  
40 al. 2015; Fernández et al. 2017). In addition, incomplete preservation and exposure of intrusive,  
41 extrusive and pyroclastic deposits permits inferences of dynamic volcanic processes only through a  
42 series of assumptions (Alfano et al. 2016; Bertelsen et al. 2021).

43 Scaled analog experiments overcome some of the above in situ measurement challenges, computer  
44 processing power limitations and associated spatial and temporal resolution constraints. Experiments  
45 provide insights into dynamic volcanic processes by systematically investigating sets of physical  
46 parameters that are critical to interpreting volcano monitoring data and forecasting eruptions and  
47 associated hazards (Appendix Table 1; e.g. Leever et al. 2014, Merle 2015, Kavanagh et al. 2018a).

48 In this contribution, we review the technological progress in the past two decades that has expanded  
49 options for quantitative analyses of multidimensional analog experiments modeling volcanic flows and  
50 deformation. We then identify three major fronts of progress that will expand the unique role of analog  
51 experiments in multidisciplinary volcanological research: improved measurements using multiple  
52 methods and instruments (multimethod), upscaling and multimethod integration. Table 1 (Appendix)

53 facilitates directly comparing scaled parameters with volcano monitoring data and testing of  
54 conceptual and numerical models. Readers can find more comprehensive reviews of analog  
55 experimental studies in volcanology, including magma chamber processes that we omit, in Mader et  
56 al. (2004, 2013), Acocella (2007), Galland et al. (2018), Kavanagh et al. (2018a) and Roche and Carazzo  
57 (2019), and Rivalta et al. (2015).

## 58 **ADVANCEMENTS IN ANALOG MODELING IN THE PAST TWO DECADES**

### 59 **Sub-surface magma migration and structural deformation**

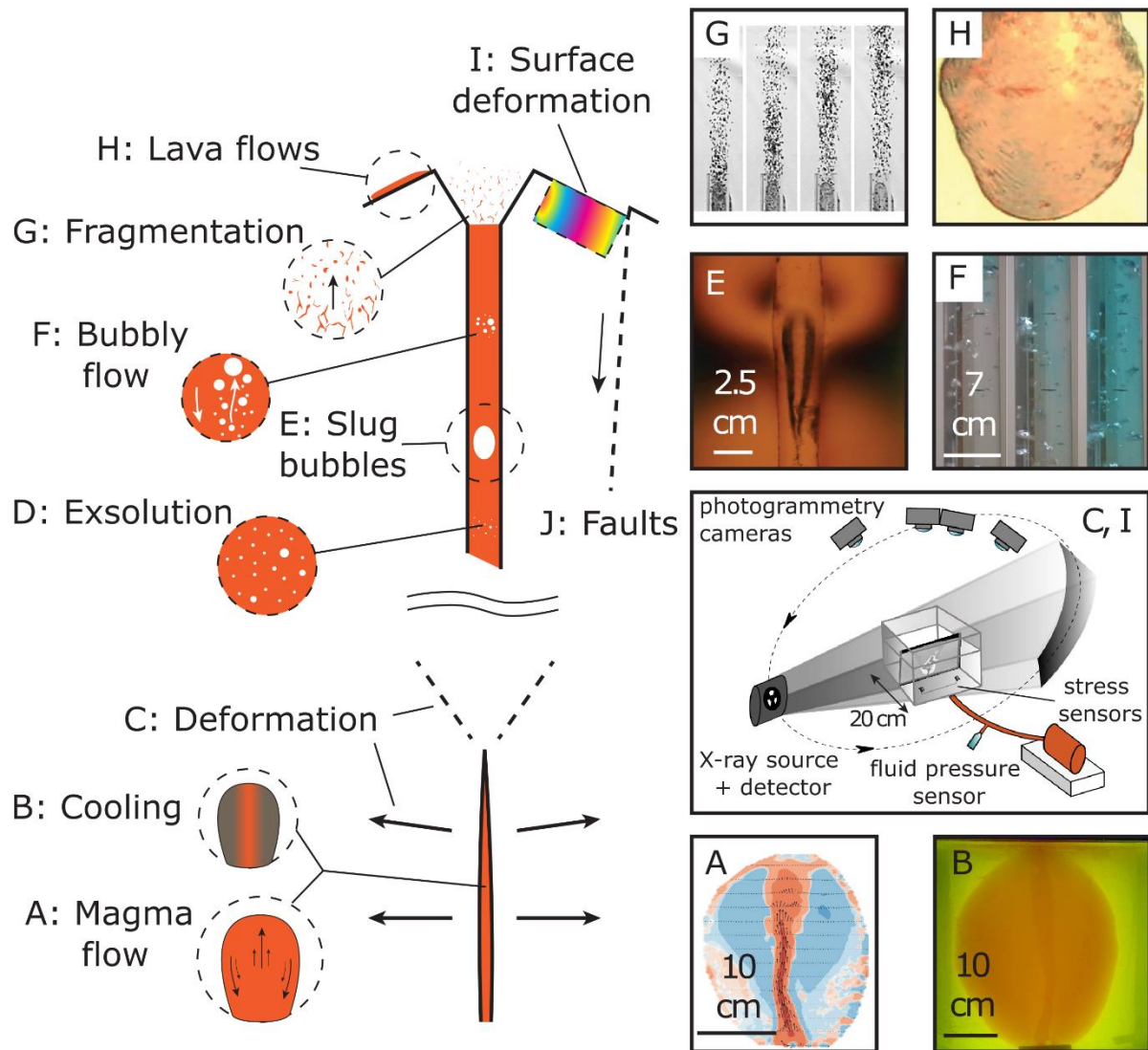
60 Magma is channelled from source regions in the Earth's mantle through volcanic and igneous plumbing  
61 systems (VIPS) towards eruption at the surface (Burchardt 2018). VIPS were previously seen as melt-  
62 dominated simple cylindrical pipes and ball-shaped "chambers". Analog experiments have helped form  
63 the current consensual model of intricate networks of geometrically complex reservoirs, conduits and  
64 sheets, filled with heterogeneous mixtures of magmatic melt, crystals and exsolved volatiles, that  
65 produce seismicity, degassing and ground deformation (Cashman and Sparks 2013; Galland et al.  
66 2018). The use of crustal rock analogs of contrasting rheologies, such as brittle-elastic gelatin vs. plastic  
67 granular materials, has underscored the control of magma and host rock properties on the three-  
68 dimensional (3D) growth of intrusions and reservoirs and associated deformation (Kavanagh et al.  
69 2018b; Bertelsen et al. 2021). Furthermore, the introduction of faulting, gravitational and far-field  
70 forces to analog experiments has helped better understand complex stress interactions between  
71 propagating magma, topographic (un)loading and tectonic forces causing acute caldera and flank  
72 collapse, or chronic gravitational deformation (e.g. Merle and Borgia 1996; Acocella 2007; Delcamp et  
73 al. 2018).

74 Modern high-speed cameras, photogrammetry, digital image analysis software and even X-ray  
75 Computed Tomography and digital volume analysis have driven a methodological evolution from  
76 qualitative descriptions to temporal quantitative monitoring of deformation fields in two dimensions  
77 (2D) against vertical cross-sections, and in 3D on experiment surfaces (e.g. Acocella 2007; Ruch et al.  
78 2012; Galland et al. 2016) and in the experiment interior (Fig. 1C; Kervyn et al. 2010; Poppe et al. 2019).  
79 More realistic physical scaling has been obtained by increasingly detailed analog material  
80 characterisation (see Table 1 of Appendix; Kavanagh et al. 2013; Reber et al. 2020; Poppe et al. 2021).  
81 Nevertheless, experiments have mostly focused on limited interactions between parameters, and  
82 experiments are rarely coupled with numerical methods.

### 83 **Conduit and surface viscous flow**

84 Shallow conduit flow encompasses a variety of interrelated processes, including volatile exsolution,  
85 decompression, multiphase flow dynamics (gas-liquid, solid-fluid, gas-liquid-solid, or two liquids of  
86 contrasting viscosity), fragmentation, lava lake dynamics, as well as lava dome extrusions and lava  
87 flows (Fig. 1). A focused study of a fundamental process minimizes complexity and dictates  
88 experimental design, which branches into three categories: depressurization, magma rheology,  
89 volumetric flux and solidification experiments.

90 Depressurization experiments load rock fragments or viscous liquids into pressurized shock tubes  
91 sealed by a releasable diaphragm. The pressure loss allows for modeling of volatile exsolution, bubble  
92 growth and fragmentation dynamics (Anilkumar et al. 1993; Spina et al. 2016). Volumetric flux  
93 experiments focus on the transport of one or more fluids through a narrow conduit, sometimes with  
94 reservoirs fixed to the ends. This allows for the study of one-, two-, and even three-phase flow  
95 dynamics, including bidirectional flow and bubble flow regimes (Seyfried and Freundt 2000;  
96 Oppenheimer et al. 2020). When a reservoir is fixed to the upper end, surface level fluctuations, funnel  
97 geometry and general flow dynamics can act as an analog for lava lakes (Witham et al. 2006; Qin et al.  
98 2018). The physics governing Strombolian eruptions have been modeled in experiments on air bubble  
99 rise through relative viscous glucose or syrup, such as the ascent and potential break up of gas slugs,  
100 the effect of conduit geometry, the very long period deformation signal, and transitions from churn to  
101 annular flow (e.g. Kueppers et al. 2006; Perugini and Kueppers 2012; Pioli et al. 2012; Azzopardi et al.  
102 2014).



105 **Figure 1.** Magma migration takes place primarily through sheet intrusions (depicted below) and conduits (above).  
 106 Individual processes illustrated in circular insets: (A) magma dynamics within a dike, (B) dike flow localization, (C)  
 107 host rock deformation, (D) volatile exsolution, (E) slug ascent, (F) bubbly flow, (G) fragmentation, (H) lava flows,  
 108 (I) (far field) surface deformation, (J) fault formation. Photo examples in square insets correspond to: (A) Pansino  
 109 et al. (in prep); (B) Pansino et al. (2019a, b); (C) Poppe et al. (2019), stress sensors in Seropian and Stix (2018),  
 110 fluid pressure sensor in Bertelsen et al. (2021); (E) Manta et al. (2019); (F) Pansino et al. (2019a, b); (G) Salvatore  
 111 et al. (2020) reproduced with permission; (J) Dieterich et al. (2017) reproduced with permission.

112  
 113 Finally, solidification experiments omit the conduit and instead model effusive activity, like lava flows,  
 114 dome extrusion and fragmentation involving external water (e.g. Fink and Griffiths 1990; Cashman et  
 115 al. 2006; Sonder et al., 2018). Whereas models can use single phase liquid or granular materials to  
 116 simulate lava flow and dome dynamics (Dieterich et al. 2015; Zorn et al. 2020), solidification  
 117 experiments rely on materials which cool and undergo heterogeneous solidification (Soule and  
 118 Cashman 2004), but also have incorporated near-real-scale furnace-heated basalt (e.g. Lev et al. 2012;  
 119 Edwards et al. 2013; Rumpf et al. 2018). Depending on the source geometry, influx, temperature and  
 120 substrate roughness, it is thus possible to investigate the velocity and geometry of such features, which  
 121 strongly resemble natural examples.

122  
 123  
 124

### 125 **Sub-aerial tephra dispersal and ground-hugging flows**

126 Above the surface, the past decade of analog experiments modeling volcanic plumes (Fig. 2a, b),  
127 explosive excavation and ballistic ejection (Fig. 2d), debris flows and pyroclastic density currents (PDCs;  
128 Fig. 2a, b) have ranged from “small-scale” benchtop flume (e.g., Roche 2012; Sher and Woods 2017;  
129 Smith et al. 2020) and tank experiments (Fig. 2b; e.g., Carazzo and Jellinek, 2012; Chojnicki et al. 2015;  
130 Gilchrist and Jellinek 2021) to “large-scale” laboratory (e.g., Lube et al. 2015; Breard and Lube 2017;  
131 Brosch and Lube 2020), and outdoor experiments (Fig. 2c, d; e.g., Graettinger et al. 2014; Sulpizio et  
132 al. 2016; Dellino et al., 2019). These experiments have established new links between micro-scale  
133 (particle scale) processes and bulk multiphase flow behavior (Fig. 2a). Two-way particle-fluid coupling  
134 processes (e.g., preferential concentration in eddies; Fig. 2a) exert controls on the mass partitioning  
135 between collapsing flows, which feed PDCs, or buoyantly rising and spreading flows, which generate  
136 plumes and ash clouds (e.g., Jessop and Jellinek 2014; Lherm and Jellinek 2019; Gilchrist and Jellinek  
137 2021). Four-way coupling (e.g., mesoscale clustering) controls the exchange of mass between dilute  
138 and dense flow regions in PDCs (e.g., Breard et al. 2016; Brosch and Lube 2020; Weit et al. 2020) and  
139 induces triboelectrification in volcanic jets that creates detectable lightning (e.g., Cimarelli et al. 2014;  
140 Van Eaton et al. 2016; Méndez Harper et al. 2021). In their densest form, volcanic flows become  
141 granular flows dominated by frictional stresses with unexpectedly high mobility and interactions with  
142 erodible substrates that can significantly affect their runout (e.g., Iverson et al. 2011; Roche et al. 2013;  
143 Bernard et al. 2014). Large-scale experiments show the expulsion of fine particle-gas mixtures from  
144 collapsing volcanic flows and have inspired improved numerical simulations and comparison to natural  
145 deposits (Graettinger et al. 2014; Valentine 2020). Due to the wide range of particle size distributions  
146 in volcanic flows, one-way and two-way particle-fluid coupling can co-exist with four-way coupling in  
147 a single system (Fig. 2e, f; e.g., Breard et al. 2016, 2017; Lube et al. 2020).

148

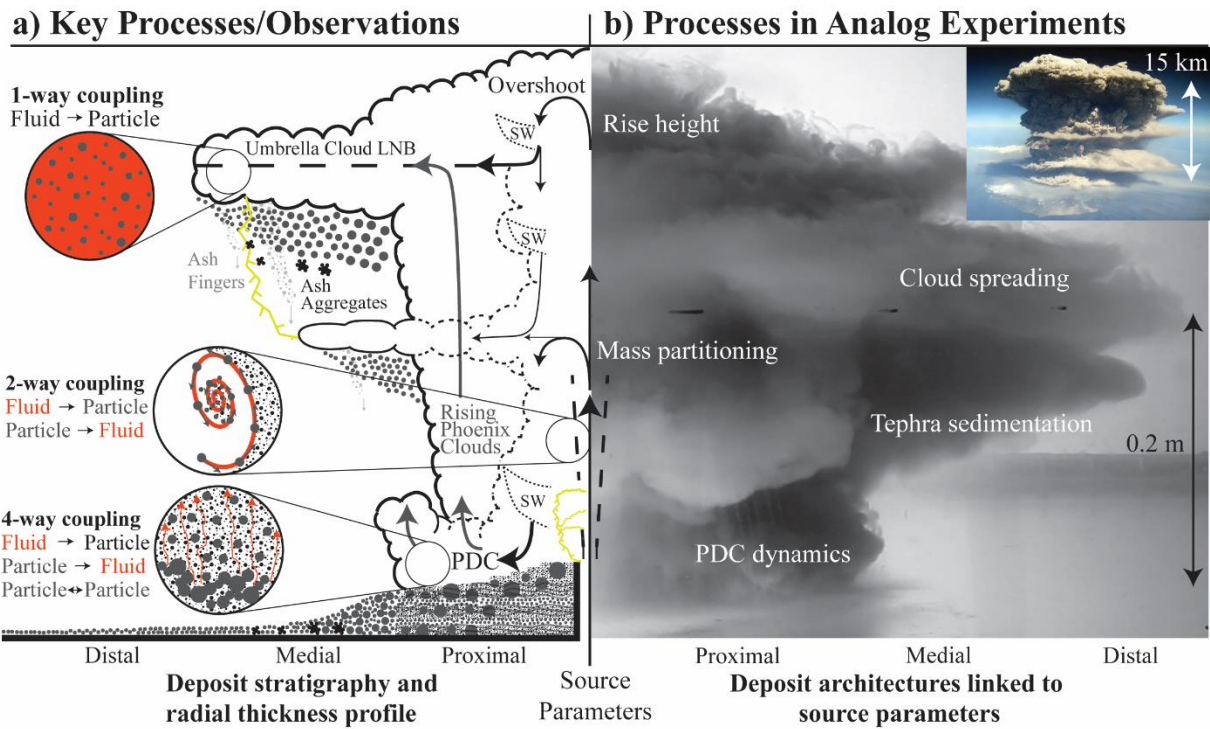
### 149 **THREE FRONTS OF PROGRESS**

150 We identify three fronts through which analog experiments can be improved to achieve the ultimate  
151 goals of volcano science (Fig. 3): understanding volcanic processes, forecasting volcanic hazards and  
152 mitigating these hazards to society.

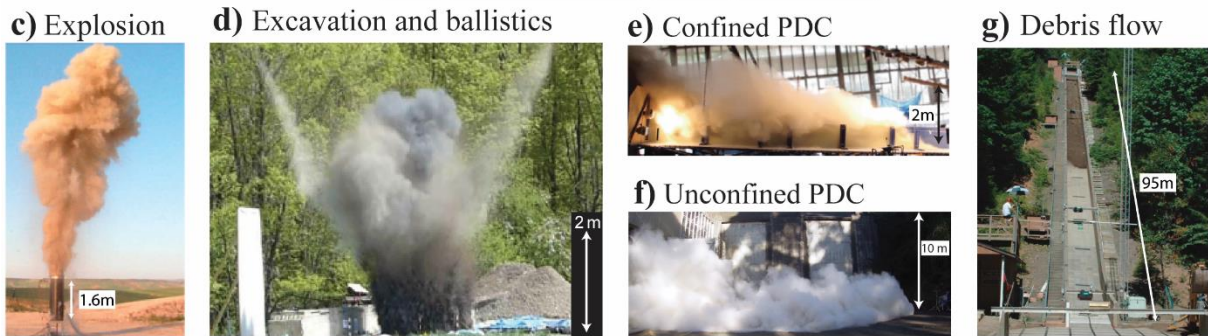
153 First, continued progress in *multimethod quantification of model parameters* that govern the dynamics  
154 of volcanic flows and deformation will address key knowledge gaps. Currently, distinct subsets of  
155 methods have been deployed at separate laboratories. With recent advancements in microcomputer  
156 technology and materials science (Zhu et al. 2020), the variety of available instruments, instrument  
157 synchronization and choice of analog materials should greatly improve. By equipping experimental  
158 setups with multisensor arrays, these improvements should aim to produce quantitative analyses of  
159 the combined effects of several modeled parameters simultaneously, including those parameters  
160 listed in Table 1 (Appendix). For example, measuring bulk flow scale properties should be combined  
161 with measuring strains and stresses of the carrying fluid or host material at the particle scale. Use of  
162 materials that achieve mechanical and thermal dynamic similarity with magma and volcanic mixtures  
163 will permit experiments to simultaneously investigate poorly understood mechanical and thermal  
164 effects (e.g., Moitra et al. 2018; Seropian and Stix 2018; Gilchrist and Jellinek 2021). Inclusive  
165 community benchmark exercises should highlight methodological uncertainties and limitations across  
166 laboratories, similar to past efforts in tectonic modeling (Klinkmüller et al. 2016). Broadening and  
167 diversifying experimental methods, incorporating more multidisciplinary teams, and replacing esoteric  
168 jargon with more widely accessible language, will foster a deeper, richer understanding of volcanic  
169 processes and encourage experimental innovation, assisted by Table 1 (Appendix).

170 Second, *upscaling experimental setups* from laboratory scale to near-real scale in dedicated warehouse  
171 or outdoor laboratories will facilitate simultaneous measurements of several parameters of volcanic  
172 processes that interact over a wide range of scales, by using a diverse and synchronized array of  
173 sensors. Building larger experiments requires a large budget and multi-year commitment, that may not  
174 be pragmatic for individual research groups.

175

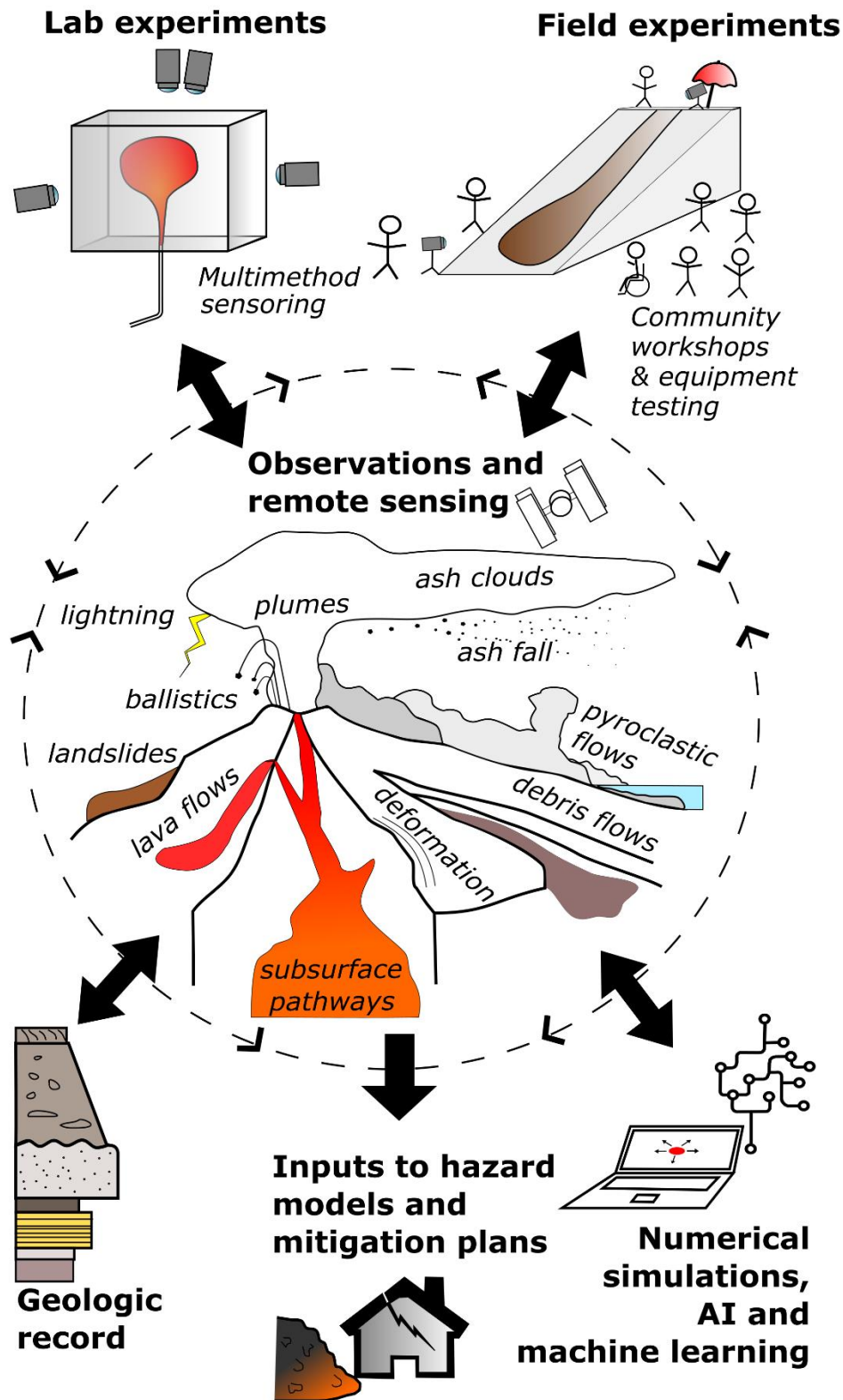


### Large-scale analogue experiments



176  
177  
178  
179  
180  
181  
182  
183  
184  
185  
186  
187  
188  
189  
190  
191  
192  
193  
194  
195  
196

**Figure 2:** **a)** Conceptual model of an explosive eruption showing key processes affecting mass transport, hazards and deposition. Exploded circles show particle-scale interactions with fluid phase that affect bulk flow dynamics. **b)** Key investigated processes in a tank-scale experiment modeling Plinian eruptions. **c)** Large-scale outdoor hot ash plume experiment in a quarry, Bari, Italy modeling the fluid mechanics of Vulcanian eruption plumes. Reprinted from Dellino et al. (2010) with permission from John Wiley and Sons. **d)** Large-scale outdoor explosion excavation cratering experiment at the U. Buffalo Geohazards Field Station modeling the mechanics of maar-diatreme eruptions. Reprinted from Graettinger et al. (2014) with permission from John Wiley and Sons. **e-f)** Warehouse and outdoor PDC flow mechanics experiment at the pyroclastic flow eruption large-scale experimental facility (PELE) at Massey U.. Reprinted from Breard et al. (2016) with permission from Springer. **g)** Large-scale outdoor debris flow flume experiments at the U.S. Geological Survey's H. J. Andrews Experimental Forest in Blue River, OR testing suites of monitoring instruments. Reprinted from Iverson et al. (2010) with permission from John Wiley and Sons.



197  
 198 **Figure 3.** Visual representation of the many ways that analog experiments across a range of scales should  
 199 integrate with other techniques in volcano science. Experiments are inspired by observations of natural  
 200 phenomena, used to test and inform the interpretation of the geologic record, and can be coupled with numerical  
 201 models to improve volcanic hazard models and crisis mitigation plans. Experiments should also be used to test  
 202 equipment and techniques for future use during eruptions, facilitate discussions at community workshops and  
 203 engage the wider public.

204 Multisensor arrays should be deployed during future large-scale explosion, lava flow, column collapse  
205 and PDC, lahar and debris flow experiments during community workshops or consortium projects  
206 supported by national and international funding bodies at existing large-scale experimental facilities  
207 (Iverson et al. 2010; Graettinger et al. 2014; Taddeucci et al. 2015; Breard et al. 2016; Allstadt et al.  
208 2020). The resulting synchronized multiparameter datasets can be used to:

- 209 1) Compare to existing multiparameter eruption datasets to better constrain governing volcanic flow  
210 parameters;
- 211 2) Inform volcano monitoring network design, so that new multisensor arrays are set up to acquire the  
212 maximum amount of information for the allotted budget.

213 The opportunity of inviting the public to attend experiments at outdoor facilities or broadly distribute  
214 experiment media on social media and to schools should be exploited more to increase public  
215 awareness of volcanic processes.

216 Third, progress in understanding volcanic processes will come from an *increased integration of*  
217 *laboratory experiments with numerical models*. Whereas experiments have demonstrated capability  
218 to model fundamental volcanic processes, knowledge gaps remain due to issues of scale or complexity.  
219 The first and second fronts will resolve scaling and upscaling, expose experimental limitations and  
220 increase compatibility of experimental data sets with geophysical monitoring data from active  
221 volcanoes. Complexity instead calls for careful planning to ensure that each component (e.g.,  
222 geometry, flow dynamics, and thermodynamics of each material) is properly scaled. Analog  
223 experiments are rarely used to guide, calibrate and validate analytical and numerical models, but have  
224 shown tremendous capability in this regard (e.g., Maccaferri et al. 2019; Esposti Ongaro et al. 2020;  
225 Mantiloni et al., 2021). Extensive and multiparameter experimental data sets can be produced that  
226 avoid the limitations of in-situ volcano monitoring data, such as a scarcity of natural events, poorly  
227 constrained source and boundary conditions, logistical and technological challenges, or slow processes  
228 that occur over a long time frame. Such synthetic data sets will support further testing and  
229 development of existing and newly-developed numerical methods, data assimilation, machine learning  
230 and artificial intelligence (AI) algorithms (e.g., Albino et al. 2020; Valentine 2020; Watson 2020).

231 In conclusion, small- to large-scale analog experiments continue to advance into sophisticated,  
232 multimethod approaches with increased measurement precision and scaling accuracy for  
233 characterizing complex multiphase volcanic processes in space and time. The three identified fronts of  
234 progress will help analog experiments continue to improve:

- 235 1) Multimethod quantification of multiphase processes;
- 236 2) Testing of multisensor volcano monitoring arrays by upscaling experiments to near-natural scales;
- 237 3) Increased integration of laboratory experiments with numerical models, machine learning and other  
238 AI algorithms.

239 These efforts will require the mobilization of an increasingly diverse and multidisciplinary community  
240 of researchers spanning all career stages, ethnic and national backgrounds in community-wide  
241 workshops and consortia supported by scientific associations and funding bodies. In this way, we  
242 foresee analog experiments as continuing to contribute uniquely to advances in our ability to model,  
243 understand and forecast volcanic hazards and to create opportunities to engage the public over the  
244 coming decade.

245  
246 **Acknowledgments** This work results from an inspiring exchange between SPo and JGi after AGU 2020 session  
247 V018. The helpful comments of G. Valentine, an anonymous reviewer and editors K. Cashman and A. Harris have  
248 greatly improved this manuscript.

249 **Author contribution** SPo led the writing; all the authors contributed equally. SPa produced Fig. 1, JGi produced  
250 Fig. 2, AGr and SPo produced Fig. 3, JGi produced Table 1 (Appendix) with input from all authors. All authors read  
251 and approved the final manuscript.

252 **Funding** SPo was supported through a frs-F.N.R.S. postdoctoral grant at UIB, and now at SRC PAS by a ULAM  
253 scholarship (Polish National Agency for Academic Exchange) and Norway Financial Mechanism grant  
254 2020/37/K/ST10/02447 (NCN Poland). JTG was supported through an NSERC Discovery grant to AM Jellinek. ECBP  
255 was supported by NSF grant 1852569 (PI: Joe Dufek). SPa was supported by a Royal Society – Newton  
256 International Fellowship, number NIF\R1\202137.



257 **REFERENCES**

- 258 Abdelmalak MM, Bulois C, Mourgues R, et al (2016) Description of new dry granular materials of variable  
259 cohesion and friction coefficient: Implications for laboratory modeling of the brittle crust. *Tectonophysics*  
260 684:39–51. <https://doi.org/10.1016/j.tecto.2016.03.003>
- 261 Acocella V (2007) Understanding caldera structure and development: An overview of analogue models compared  
262 to natural calderas. *Earth-Science Rev* 85:125–160. <https://doi.org/10.1016/j.earscirev.2007.08.004>
- 263 Albino F, Biggs J, Yu C, Li Z (2020) Automated Methods for Detecting Volcanic Deformation Using Sentinel-1 InSAR  
264 Time Series Illustrated by the 2017–2018 Unrest at Agung, Indonesia. *J Geophys Res Solid Earth* 125:1–40.  
265 <https://doi.org/10.1029/2019JB017908>
- 266 Alfano F, Bonadonna C, Watt S, et al (2016) Reconstruction of total grain size distribution of the climactic phase  
267 of a long-lasting eruption: the example of the 2008–2013 Chaitén eruption. *Bull Volcanol* 78:.  
268 <https://doi.org/10.1007/s00445-016-1040-5>
- 269 Allstadt KE, Farin M, Iverson RM, et al (2020) Measuring Basal Force Fluctuations of Debris Flows Using Seismic  
270 Recordings and Empirical Green's Functions. *J Geophys Res Earth Surf* 125:.  
271 <https://doi.org/10.1029/2020JF005590>
- 272 Andrews BJ, Manga M (2012) Experimental study of turbulence, sedimentation, and coignimbrite mass  
273 partitioning in dilute pyroclastic density currents. *J Volcanol Geotherm Res* 225:30-44  
274 <https://doi.org/10.1016/j.jvolgeores.2012.02.011>
- 275 Anilkumar AV, Sparks RSJ, Sturtevant B (1993) Geological implications and applications of high-velocity two-phase  
276 flow experiments. *J Volcanol Geotherm Res* 56:145–160. [https://doi.org/https://doi.org/10.1016/0377-  
277 0273\(93\)90056-W](https://doi.org/https://doi.org/10.1016/0377-0273(93)90056-W)
- 278 Azzopardi BJ, Pioli L, Abdulkareem LA (2014) The properties of large bubbles rising in very viscous liquids in  
279 vertical columns. *Int J Multiph Flow* 67:160-173. <https://doi.org/10.1016/j.ijmultiphaseflow.2014.08.013>
- 280 Bernard J, Kelfoun K, Le Pennec J-L, Vallejo Vargas S (2014) Pyroclastic flow erosion and bulking processes;  
281 comparing field-based vs. modeling results at Tungurahua Volcano, Ecuador. *Bull Volcanol* 76(9):1-16,  
282 <doi:http://dx.doi.org/10.1007/s00445-014-0858-y>
- 283 Bertelsen HS, Guldstrand F, Sigmundsson F, et al (2021) Beyond elasticity: Are Coulomb properties of the Earth's  
284 crust important for volcano geodesy? *J Volcanol Geotherm Res* 410:.  
285 <https://doi.org/10.1016/j.jvolgeores.2020.107153>
- 286 Breard ECP, Lube G (2017) Inside pyroclastic density currents – uncovering the enigmatic flow structure and  
287 transport behaviour in large-scale experiments. *Earth Planet Sci Lett* 458:22-36.  
288 <doi:http://dx.doi.org/10.1016/j.epsl.2016.10.016>.
- 289 Breard ECP, Lube G, Jones JR, et al (2016) Coupling of turbulent and non-turbulent flow regimes within pyroclastic  
290 density currents. *Nat Geosci* 9:767–771. <https://doi.org/10.1038/ngeo2794>
- 291 Breard ECP, Dufek J, Lube G (2017) Enhanced Mobility in Concentrated Pyroclastic Density Currents: An  
292 Examination of a Self-Fluidization Mechanism. *Geophys R Lett* 45:654–664. <doi:10.1002/2017GL075759>.
- 293 Breard EC, Jones JR, Fullard L, et al (2019) The permeability of volcanic mixtures—implications for pyroclastic  
294 currents. *J Geophys Res Solid Earth* 124(2):1343-60 <https://doi.org/10.1029/2018JB016544>
- 295 Breard EC, Dufek J, Fullard L, Carrara A (2020) The Basal Friction Coefficient of Granular Flows With and Without  
296 Excess Pore Pressure: Implications for Pyroclastic Density Currents, Water-Rich Debris Flows, and Rock and  
297 Submarine Avalanches. *J Geophys Res Solid Earth* 125(12):e2020JB020203  
298 <https://doi.org/10.1029/2020JB020203>
- 299 Brosch E, Lube G (2020) Spatiotemporal sediment transport and deposition processes in experimental dilute  
300 pyroclastic density currents. *J Volc Geotherm Res* 401:106946  
301 <https://doi.org/10.1016/j.jvolgeores.2020.106946>
- 302 Brothelande E, Peltier A, Got JL, et al (2016) Constraints on the source of resurgent doming inferred from  
303 analogue and numerical modeling — Implications on the current feeding system of the Yenkahe dome–  
304 Yasur volcano complex (Vanuatu). *J Volcanol Geotherm Res* 322:225–240.  
305 <https://doi.org/10.1016/j.jvolgeores.2015.11.023>
- 306 Burchardt S (2018) Introduction to Volcanic and Igneous Plumbing Systems—Developing a Discipline and  
307 Common Concepts. In: Burchardt S (ed) *Volcanic and Igneous Plumbing Systems*. Elsevier, Amsterdam, pp  
308 1–12
- 309 Byrne PK, Holohan EP, Kervyn M, et al (2013) A sagging-spreading continuum of large volcano structure. *Geology*  
310 41:339–342. <https://doi.org/10.1130/G33990.1>
- 311 Cagnoli B, Manga M (2003) Pumice-pumice collisions and the effect of the impact angle. *Geophys Res Lett* 30(12)  
312 <https://doi.org/10.1029/2003GL017421>
- 313 Carazzo G, Jellinek AM (2012) A new view of the dynamics, stability and longevity of volcanic clouds. *Earth Planet*

314 Sci Lett 325:39–51. <https://doi.org/https://doi.org/10.1016/j.epsl.2012.01.025>

315 Carazzo G, Girault F, Aubry T, et al (2014) Laboratory experiments of forced plumes in a density-stratified  
316 crossflow and implications for volcanic plumes. *Geophys Res Lett* 41(24):8759–66  
317 <https://doi.org/10.1002/2014GL061887>

318 Carazzo G, Kaminski E, Tait S (2015) The timing and intensity of column collapse during explosive volcanic  
319 eruptions. *Earth Planet Sci Lett* 411:208–17 <https://doi.org/10.1016/j.epsl.2014.12.006>

320 Carey SN, Sigurdsson H, Sparks RS (1988) Experimental studies of particle-laden plumes. *J Geophys Res Solid  
321 Earth* 93(B12):15314–28 <https://doi.org/10.1029/JB093iB12p15314>

322 Cashman KV, Stephen R, Sparks J (2013) How volcanoes work: A 25 year perspective. *Bull Geol Soc Am* 125:664–  
323 690. <https://doi.org/10.1130/B30720.1>

324 Cashman KV, Kerr RC, Griffiths RW (2006) A laboratory model of surface crust formation and disruption on lava  
325 flows through non-uniform channels. *Bull Volcanol* 68:753–770. <https://doi.org/10.1007/s00445-005-0048-z>

326

327 Chojnicki KN, Clarke AB, Phillips JC, Adrian RJ (2015). Rise dynamics of unsteady laboratory jets with implications  
328 for volcanic plumes. *Earth Planet Sci Lett* 412:186–196. <https://doi.org/10.1016/j.epsl.2014.11.046>

329 Cimarelli C, Alatorre-Ibargüengoitia MA, Kueppers U, et al (2014) Experimental generation of volcanic lightning.  
330 *Geology* 42:79–82. <https://doi.org/10.1130/G34802.1>

331 Delcamp A, van Wyk de Vries B, James MR (2008) The influence of edifice slope and substrata on volcano  
332 spreading. *J Volcanol Geotherm Res* 177:925–943. <https://doi.org/10.1016/j.jvolgeores.2008.07.014>

333 Delcamp A, Poppe S, Detienne M, Paguican EMR (2018) Destroying a Volcanic Edifice—Interactions Between  
334 Edifice Instabilities and the Volcanic Plumbing System. In: *Volcanic and Igneous Plumbing Systems*. Elsevier,  
335 pp 231–257

336 Dellino P, Büttner R, Dioguardi F, et al (2010) Experimental evidence links volcanic particle characteristics to  
337 pyroclastic flow hazard. *Earth Planet Sci Lett* 295(1-2):314–20 <https://doi.org/10.1016/j.epsl.2010.04.022>

338 Dellino P, Dioguardi F, Doronzo DM, Mele D (2019) The Entrainment Rate of Non-Boussinesq Hazardous  
339 Geophysical Gas-Particle Flows: An Experimental Model With Application to Pyroclastic Density Currents.  
340 *Geophys Res Lett* 46:12851–12861. <https://doi.org/10.1029/2019GL084776>

341 Dellino P, Mele D, Bonasia R, et al (2005) The analysis of the influence of pumice shape on its terminal velocity.  
342 *Geophys Res Lett* 32(21) <https://doi.org/10.1029/2005GL023954>

343 Dellino P, Zimanowski B, Büttner R, et al (2007) Large-scale experiments on the mechanics of pyroclastic flows:  
344 Design, engineering, and first results. *J Geophys Res Solid Earth* 112(B4)  
345 <https://doi.org/10.1029/2006JB004313>

346 Derrien A, Taisne B (2019) 360 intrusions in a miniature volcano: Birth, growth, and evolution of an analog edifice.  
347 *Front Earth Sci* 7:.. <https://doi.org/10.3389/feart.2019.00019>

348 Dietterich HR, Cashman KV, Rust AC, Lev E (2015) Diverting lava flows in the lab. *Nature geoscience* 8(7):494–496.  
349 <https://doi.org/10.1038/ngeo2470>

350 Dietterich HR, Lev E, Chen J, et al (2017) Benchmarking computational fluid dynamics models of lava flow  
351 simulation for hazard assessment, forecasting, and risk management. *J Appl Volcanol* 6:.  
352 <https://doi.org/10.1186/s13617-017-0061-x>

353 Druitt TH, Avaré G, Bruni G, et al (2007) Gas retention in fine-grained pyroclastic flow materials at high  
354 temperatures. *Bull Volcanol* 69(8):881–901 <https://doi.org/10.1007/s00445-007-0116-7>

355 Dufek J, Wexler J, Manga M (2009) Transport capacity of pyroclastic density currents: Experiments and models  
356 of substrate-flow interaction. *J Geophys Res Solid Earth* 114(B11) <https://doi.org/10.1029/2008JB006216>

357 Dürig T, Gudmundsson MT, Dellino P (2015) Reconstruction of the geometry of volcanic vents by trajectory  
358 tracking of fast ejecta—the case of the Eyjafjallajökull 2010 eruption (Iceland). *Earth Planets Space* 67(1):1–  
359 8 <https://doi.org/10.1186/s40623-015-0243-x>

360 Edwards BR, Karson J, Wysocki R, et al (2013) Insights on lava–ice/snow interactions from large-scale basaltic  
361 melt experiments. *Geology* 41(8):851–4. <https://doi.org/10.1130/G34305.1>

362 Esposti Ongaro T, Cerminara M, Charbonnier SJ, et al (2020) A framework for validation and benchmarking of  
363 pyroclastic current models. *Bull Volcanol* 82(6):51. <https://doi.org/10.1007/s00445-020-01388-2>.

364 Fauria KE, Manga M (2018) Pyroclast cooling and saturation in water. *J Volcanol Geotherm Res* 362:17–31  
365 <https://doi.org/10.1016/j.jvolgeores.2018.07.002>

366 Fernández J, Pepe A, Poland MP, Sigmundsson F (2017) Volcano Geodesy: Recent developments and future  
367 challenges. *J Volcanol Geotherm Res* 344:1–12. <https://doi.org/10.1016/j.jvolgeores.2017.08.006>

368 Fink JH, Griffiths RW (1990) Radial spreading of viscous-gravity currents with solidifying crust. *J Fluid Mech*  
369 221:485–509. <https://doi.org/10.1017/S0022112090003640>

370 Gailler L-S, Lénat J-F, Lambert M, et al (2009) Gravity structure of Piton de la Fournaise volcano and inferred mass

371 transfer during the 2007 crisis. *J Volcanol Geotherm Res* 184:31–48.  
372 <https://doi.org/10.1016/j.jvolgeores.2009.01.024>

373 Galland O, Cobbold PR, Hallot E, et al (2006) Use of vegetable oil and silica powder for scale modelling of  
374 magmatic intrusion in a deforming brittle crust. *Earth Planet Sci Lett* 243:786–804.  
375 <https://doi.org/10.1016/j.epsl.2006.01.014>

376 Galland O, Burchardt S, Hallot E, et al (2014) Toward a unified dynamic model for dykes and cone sheets in  
377 volcanic systems. 16:5468

378 Galland O, Bertelsen HS, Guldstrand F, et al (2016) Application of open-source photogrammetric software  
379 MicMac for monitoring surface deformation in laboratory models. *J Geophys Res Earth* 1–21.  
380 <https://doi.org/10.1002/2015JB012755>.Received

381 Galland O, Holohan EP, van Wyk de Vries B, Burchardt S (2018) Laboratory Modelling of Volcano Plumbing  
382 Systems: A Review. In: Breiterkreuz C, Rocchi S (eds) *Physical Geology of Shallow Magmatic Systems - Dykes,*  
383 *Sills and Laccoliths.* Springer Berlin Heidelberg, pp 147–214

384 Gilchrist JT, Jellinek AM (2021) Sediment waves and the gravitational stability of volcanic jets. *Bull Volcanol* 83:.  
385 <https://doi.org/10.1007/s00445-021-01472-1>

386 Gilchrist J, Mergny C, Rowell CR, et al (2020) Characterization of source unsteadiness and entrainment into  
387 explosive eruptions using laboratory-and field-based methods. *AGU Fall Meeting Abstracts 2020:V008-*  
388 *0014.* <https://ui.adsabs.harvard.edu/abs/2020AGUFMV008.0014G>

389 Gonnermann HM (2015) Magma fragmentation. *Annu Rev Earth Planet Sci* 43:431–458.  
390 <https://doi.org/10.1146/annurev-earth-060614-105206>

391 Gonnermann HM, Giachetti T, Fliedner C, et al (2017) Permeability during magma expansion and compaction. *J*  
392 *Geophys Res Solid Earth* 122(12):9825-48 <https://doi.org/10.1002/2017JB014783>

393 Graettinger AH (2018) Trends in maar crater size and shape using the global Maar Volcano Location and Shape  
394 (MaarVLS) database. *J Volcanol Geotherm Res* 357:1-3. <https://doi.org/10.1016/j.jvolgeores.2018.04.002>

395 Graettinger AH, Valentine GA (2017) Evidence for the relative depths and energies of phreatomagmatic  
396 explosions recorded in tephra rings. *Bull Volcanol* 79(12):1-21. [https://doi.org/10.1007/s00445-017-1177-](https://doi.org/10.1007/s00445-017-1177-x)  
397 *x*

398 Graettinger AH, Valentine GA, Sonder I, et al (2014) Maar-diatreme geometry and deposits: Subsurface blast  
399 experiments with variable explosion depth. *Geochemistry, Geophys Geosystems* 15:740–764.  
400 <https://doi.org/10.1002/2013GC005198>

401 Gregg TK, Fink JH (2000) A laboratory investigation into the effects of slope on lava flow morphology. *J Volcanol*  
402 *Geotherm Res* 96(3-4):145-59 [https://doi.org/10.1016/S0377-0273\(99\)00148-1](https://doi.org/10.1016/S0377-0273(99)00148-1)

403 Griffiths RW (2000) The dynamics of lava flows. *Ann Rev Fluid Mech* 32(1):477-518.  
404 <https://doi.org/10.1146/annurev.fluid.32.1.477>

405 Grosse P, Poppe S, Delcamp A, et al (2020) Volcano growth versus deformation by strike-slip faults:  
406 Morphometric characterization through analogue modelling. *Tectonophysics.*  
407 <https://doi.org/10.1016/j.tecto.2020.228411>

408 Guldstrand, F., Burchardt, S., Hallot, E., Galland, O. (2017) Dynamics of surface deformation induced by dikes and  
409 cone sheets in a cohesive Coulomb brittle crust. *J Geophys Res Solid Earth* 122(10):8511-8524.  
410 <https://doi.org/10.1002/2017JB014346>

411 Hartlieb P, Toifl M, Kuchar F, et al (2016) Thermo-physical properties of selected hard rocks and their relation to  
412 microwave-assisted comminution. *Miner Eng* 91:34–41. <https://doi.org/10.1016/j.mineng.2015.11.008>

413 Holohan EP, Van Wyk de Vries B, Troll VR (2008) Analogue models of caldera collapse in strike-slip tectonic  
414 regimes. *Bull Volcanol* 70:773–796. <https://doi.org/10.1007/s00445-007-0166-x>

415 Huppert HE (1982) The propagation of two-dimensional and axisymmetric viscous gravity currents over a rigid  
416 horizontal surface. *J Fluid Mech* 121:43-58. <https://doi.org/10.1017/S0022112082001797>

417 Huppert HE, Sparks, RSJ (1985) Cooling and contamination of mafic and ultramafic magmas during ascent through  
418 continental crust. *Earth Planet Sci Lett* 74(4):371-386. [https://doi.org/10.1016/S0012-821X\(85\)80009-1](https://doi.org/10.1016/S0012-821X(85)80009-1)

419 Huppert HE, Sparks RSJ, Turner JS, Arndt NT (1984) Emplacement and cooling of komatiite lavas. *Nature*  
420 309(5963):19-22. <https://doi.org/10.1038/309019a0>

421 Iverson RM (2012) Elementary theory of bed-sediment entrainment by debris flows and avalanches. *J Geophys*  
422 *Res Earth Surf* 117(F3). <https://doi.org/10.1029/2011JF002189>

423 Iverson RM, Logan M, LaHusen RG, Berti M (2010) The perfect debris flow? Aggregated results from 28 large-  
424 scale experiments. *J Geophys Res* 115:.. <https://doi.org/10.1029/2009jf001514>

425 Iverson RM, Reid ME, Logan M, et al (2011) Positive feedback and momentum growth during debris-flow  
426 entrainment of wet bed sediment. *Nat Geosci* 4:116–121. <https://doi.org/10.1038/ngeo1040>

427 Jessop D, Jellinek A (2014) Effects of particle mixtures and nozzle geometry on entrainment into volcanic jets.

428 Geophys Res Lett 41(11):3858–3863. <https://doi.org/10.1002/2014GL060059>

429 Jessop DE, Gilchrist J, Jellinek AM, Roche O (2016) Are eruptions from linear fissures and caldera ring dykes more  
430 likely to produce pyroclastic flows? *Earth Planet Scie Lett* 454:142–53.  
431 <https://doi.org/10.1016/j.epsl.2016.09.005>

432 Kavanagh JL, Menand T, Daniels KA (2013) Gelatine as a crustal analogue: Determining elastic properties for  
433 modelling magmatic intrusions. *Tectonophysics* 582:101–111.  
434 <https://doi.org/10.1016/j.tecto.2012.09.032>

435 Kavanagh JL, Engwell S, Martin S (2018a) A review of analogue and numerical modelling in volcanology. *Solid  
436 Earth* 9:531–571. <https://doi.org/10.5194/se-9-531-2018>

437 Kavanagh JL, Burns AJ, Hilmi Hazim S, et al (2018b) Challenging dyke ascent models using novel laboratory  
438 experiments: Implications for reinterpreting evidence of magma ascent and volcanism. *J Volcanol  
439 Geotherm Res* 354:87–101. <https://doi.org/10.1016/j.jvolgeores.2018.01.002>

440 Kervyn M, Boone MN, de Vries B van W, et al (2010) 3D imaging of volcano gravitational deformation by  
441 computerized X-ray micro-tomography. *Geosphere* 6:482–498. <https://doi.org/10.1130/ges00564.1>

442 Kieffer SW, Sturtevant B (1984) Laboratory studies of volcanic jets. *J Geophys Res Solid Earth* 89(B10):8253–68.  
443 <https://doi.org/10.1029/JB089iB10p08253>

444 Kilgour G, Manville V, Della Pasqua F, et al (2010) The 25 September 2007 eruption of Mount Ruapehu, New  
445 Zealand: directed ballistics, surtseyan jets, and ice-slurry lahars. *J Volcanol Geotherm Res* 191(1-2):1-4.  
446 <https://doi.org/10.1016/j.jvolgeores.2009.10.015>

447 Klinkmüller M, Schreurs G, Rosenau M, Kemnitz H (2016) Properties of granular analogue model materials: A  
448 community wide survey. *Tectonophysics* 684:23–38. <https://doi.org/10.1016/j.tecto.2016.01.017>

449 Kueppers U, Scheu B, Spieler O, Dingwell DB (2006) Fragmentation efficiency of explosive volcanic eruptions: A  
450 study of experimentally generated pyroclasts. *J Volcanol Geotherm Res* 153(1-2):125-135.  
451 <https://doi.org/10.1016/j.jvolgeores.2005.08.006>

452 Leever K, Galland O, Accocella V (2014) The science behind laboratory-scale models of the earth. *Eos (Washington  
453 DC)* 95:30. <https://doi.org/10.1002/2014EO030008>

454 Lev E, Spiegelman M, Wysocki RJ, Karson JA (2012) Investigating lava flow rheology using video analysis and  
455 numerical flow models. *J Volcanol Geotherm Res* 247:62-73.  
456 <https://doi.org/10.1016/j.jvolgeores.2012.08.002>

457 Lherm V, Jellinek AM (2019) Experimental constraints on the distinct effects of ash, lapilli, and larger pyroclasts  
458 on entrainment and mixing in volcanic plumes. *Bull Volcanol* 81(12):73. <https://doi.org/10.1007/s00445-019-1329-2>

459

460 Lister J, Kerr R (1991) Fluid-Mechanical Models of Crack Propagation and Their Application to Magma Transport  
461 in Dykes. *J Geophys Res* 96:10,049-10,077. <https://doi.org/10.1029/91JB00600>

462 Loughlin SC, Sparks S, Brown SK, et al (2015) *Global volcanic hazards and risk*. Cambridge University Press,  
463 Cambridge

464 Lube G, Breard EC, Cronin SJ et al (2014) Dynamics of surges generated by hydrothermal blasts during the 6  
465 August 2012 Te Maari eruption, Mt. Tongariro, New Zealand. *J Volcanol Geotherm Res* 286:348–366.  
466 <https://doi.org/10.1016/j.jvolgeores.2014.05.010>

467 Lube G, Breard ECP, Cronin SJ, Jones J (2015) Synthesizing large-scale pyroclastic flows: Experimental design,  
468 scaling, and first results from PELE. *J Geophys Res Solid Earth* 120:1487–1502.  
469 <https://doi.org/10.1002/2014JB011666>

470 Lube G, Breard ECP, Esposti-Ongaro T, et al (2020) Multiphase flow behaviour and hazard prediction of pyroclastic  
471 density currents. *Nat Rev Earth Environ* 1:348–365. <https://doi.org/10.1038/s43017-020-0064-8>

472 Maccaferri F, Smittarello D, Pinel V, Cayol V (2019) On the Propagation Path of Magma-Filled Dikes and  
473 Hydrofractures: The Competition Between External Stress, Internal Pressure, and Crack Length.  
474 *Geochemistry, Geophys Geosystems* 20:2064–2081. <https://doi.org/10.1029/2018GC007915>

475 Mader HM, Manga M, Koyaguchi T (2004) The role of laboratory experiments in volcanology. *J Volcanol  
476 Geotherm Res* 129:1–5. [https://doi.org/10.1016/S0377-0273\(03\)00228-2](https://doi.org/10.1016/S0377-0273(03)00228-2)

477 Mader HM, Llewelin EW, Mueller SP (2013) The rheology of two-phase magmas: A review and analysis. *J Volcanol  
478 Geotherm Res* 257:135–158. <https://doi.org/10.1016/J.JVOLGEORES.2013.02.014>

479 Manta F, Emadzadeh A, Taisne B (2019) New Insight Into a Volcanic System: Analogue Investigation of Bubble-  
480 Driven Deformation in an Elastic Conduit. *J Geophys Res Solid Earth* 124:11274–11289.  
481 <https://doi.org/10.1029/2019JB017665>

482 Mantiloni L, Davis T, Gaete Rojas AB, Rivalta E (2021) Stress Inversion in a Gelatin Box: Testing Eruptive Vent  
483 Location Forecasts With Analog Models. *Geophys Res Lett* 48:1–11.  
484 <https://doi.org/10.1029/2020GL090407>

485 Mathieu L, van Wyk de Vries B, Holohan EP, Troll VR (2008) Dykes, cups, saucers and sills: Analogue experiments  
486 on magma intrusion into brittle rocks. *Earth Planet Sci Lett* 271:1–13.  
487 <https://doi.org/10.1016/j.epsl.2008.02.020>

488 Méndez Harper J, Cimarelli C, Cigala V, et al (2021) Charge injection into the atmosphere by explosive volcanic  
489 eruptions through triboelectrification and fragmentation charging *Earth Planet Sci Lett* 574:117162.  
490 <https://doi.org/10.1016/j.epsl.2021.117162>.

491 Meredith PG, Atkinson BK (1985) Fracture toughness and subcritical crack growth during high-temperature  
492 tensile deformation of Westerly granite and Black gabbro. *Phys Earth Planet Inter* 39:33–51.  
493 [https://doi.org/10.1016/0031-9201\(85\)90113-X](https://doi.org/10.1016/0031-9201(85)90113-X)

494 Merle O (2015) The scaling of experiments on volcanic systems. *Front Earth Sci* 3:1–15.  
495 <https://doi.org/10.3389/feart.2015.00026>

496 Merle O, Borgia A (1996) Scaled experiments of volcanic spreading. *J Geophys Res* 101:13805.  
497 <https://doi.org/10.1029/95JB03736>

498 Moitra P, Sonder I, Valentine GA (2018) Effects of Size and Temperature-Dependent Thermal Conductivity on the  
499 Cooling of Pyroclasts in Air. *Geochem Geophys Geosystems* 19(10):3623–3636.  
500 <https://doi.org/10.1029/2018GC007510>.

501 Neilsen TB, Matoza RS, Maher S, et al (2019) Preliminary analyses of seismo-acoustic wave propagation in  
502 outdoor field-scale analog volcanic explosions. *J Acoustic Soc Am* 145(3):1869.  
503 <https://doi.org/10.1121/1.5101754>

504 Oppenheimer J, Rust AC, Cashman KV, Sandnes B (2015) Gas migration regimes and outgassing in particle-rich  
505 suspensions. *Frontiers Phys* 3:60. <https://doi.org/10.3389/fphy.2015.00060>

506 Oppenheimer J, Capponi A, Cashman K V, et al (2020) Analogue experiments on the rise of large bubbles through  
507 a solids-rich suspension: A “weak plug” model for Strombolian eruptions. *Earth Planet Sci Lett* 531:115931.  
508 <https://doi.org/10.1016/J.EPSL.2019.115931>

509 Orescanin MM, Prisco D, Austin JM, Kieffer SW (2014) Flow of supersonic jets across flat plates: Implications for  
510 ground-level flow from volcanic blasts. *J Geophys Res Solid Earth* 119(4):2976–87.  
511 <https://doi.org/10.1002/2013JB010743>

512 Ort MH, Lefebvre NS, Neal CA, et al (2018) Linking the Ukinrek 1977 maar-eruption observations to the tephra  
513 deposits: new insights into maar depositional processes. *J Volcanol Geotherm Res* 360:36–60. <https://doi.org/10.1016/j.jvolgeores.2018.07.005>.

515 Pansino S, Taisne B (2019) How magmatic storage regions attract and repel propagating dikes. *J Geophys Res*  
516 *Solid Earth* 124(1):274–90. <https://doi.org/10.1029/2018JB016311>

517 Pansino S, Calder ES, Menand T (2019a) Experimental analysis of bubble-driven magma motion in the conduit,  
518 for persistently active, open-vent volcanoes. *Bull Volcanol* 81:. <https://doi.org/10.1007/s00445-019-1339-0>

519

520 Pansino S, Emadzadeh A, Taisne B (2019b) Dike Channelization and Solidification: Time Scale Controls on the  
521 Geometry and Placement of Magma Migration Pathways. *J Geophys Res Solid Earth* 124(9):9580–9599.  
522 <https://doi.org/10.1029/2019JB018191>

523 Perugini D, Kueppers U (2012) Fractal analysis of experimentally generated pyroclasts: a tool for volcanic hazard  
524 assessment. *Acta Geophys* 60(3):682–698. <https://doi.org/10.2478/s11600-012-0019-7>

525 Pioli L, Bonadonna C, Azzopardi BJ, et al (2012) Experimental constraints on the outgassing dynamics of basaltic  
526 magmas. *J Geophys R: Solid Earth* 117(B3). <https://doi.org/10.1029/2011JB008392>

527 Poppe S, Holohan EP, Pauwels E, et al (2015) Sinkholes, pit craters, and small calderas: Analog models of  
528 depletion-induced collapse analyzed by computed X-ray microtomography. *Bull Geol Soc Am* 127:281–296.  
529 <https://doi.org/10.1130/B30989.1>

530 Poppe S, Holohan EP, Galland O, et al (2019) An Inside Perspective on Magma Intrusion: Quantifying 3D  
531 Displacement and Strain in Laboratory Experiments by Dynamic X-Ray Computed Tomography. *Front Earth*  
532 *Sci* 7:62. <https://doi.org/10.3389/feart.2019.00062>

533 Poppe S, Holohan EP, Rudolf M, et al (2021) Mechanical properties of quartz sand and gypsum powder (plaster)  
534 mixtures: Implications for laboratory model analogues for the Earth’s upper crust. *Tectonophysics*  
535 814:228976. <https://doi.org/10.1016/J.TECTO.2021.228976>

536 Qin Z, Soldati A, Velazquez Santana LC, et al (2018) Slug Stability in Flaring Geometries and Ramifications for Lava  
537 Lake Degassing. *J Geophys Res Solid Earth* 123:10,431–10,448. <https://doi.org/10.1029/2018JB016113>

538 Reber JE, Cooke ML, Dooley TP (2020) What model material to use? A Review on rock analogs for structural  
539 geology and tectonics. *Earth-Science Reviews* 202:103107.  
540 <https://doi.org/10.1016/j.earscirev.2020.103107>

541 Ripepe M, Rossi M, Saccorotti G (1993) Image processing of explosive activity at Stromboli. *J Volcanol Geotherm*

542 Res 54(3-4):335-51. [https://doi.org/10.1016/0377-0273\(93\)90071-X](https://doi.org/10.1016/0377-0273(93)90071-X)

543 Rivalta E, Büttinger M, Dahm T (2005) Buoyancy-driven fracture ascent: Experiments in layered gelatine. *J*

544 *Volcanol Geotherm Res* 144:273–285. <https://doi.org/10.1016/j.jvolgeores.2004.11.030>

545 Rivalta E, Taisne B, Bungler AP, Katz RF (2015) A review of mechanical models of dike propagation: Schools of

546 thought, results and future directions. *Tectonophysics* 638:1–42.

547 <https://doi.org/10.1016/j.tecto.2014.10.003>

548 Roche O (2012) Depositional processes and gas pore pressure in pyroclastic flows: An experimental perspective.

549 *Bull Volcanol* 74:1807–1820. <https://doi.org/10.1007/s00445-012-0639-4>

550 Roche O, Carazzo G (2019) The contribution of experimental volcanology to the study of the physics of eruptive

551 processes, and related scaling issues: A review. *J Volcanol Geotherm Res* 384:103–150.

552 <https://doi.org/10.1016/J.JVOLGEORES.2019.07.011>

553 Roche O, Druitt TH, Merle O (2000) Experimental study of caldera formation. *J Geophys Res* 105:395.

554 <https://doi.org/10.1029/1999JB900298>

555 Roche O, Niño Y, Mangeney A, et al (2013) Dynamic pore-pressure variations induce substrate erosion by

556 pyroclastic flows. *Geology* 41:1107–1110. <https://doi.org/10.1130/G34668.1>

557 Romine WL, Whittington AG, Nabelek PI, Hofmeister AM (2012) Thermal diffusivity of rhyolitic glasses and melts:

558 effects of temperature, crystals and dissolved water. *Bull Volcanol* 74(10):2273–2287.

559 <https://doi.org/10.1007/s00445-012-0661-6>

560 Rowell CR, Jellinek M, Gilchrist J (2020) Tracking time-dependent eruption source unsteadiness and local

561 entrainment in ground-based thermal imagery using spectral-clustering. *AGU Fall Meeting Abstracts*

562 2020:V008-0015. <https://ui.adsabs.harvard.edu/abs/2020AGUFMV008.0015R>

563 Ruch J, Acocella V, Geshi N, et al (2012) Kinematic analysis of vertical collapse on volcanoes using experimental

564 models time series. *J Geophys Res* 117:B07301. <https://doi.org/10.1029/2012JB009229>

565 Rumpf ME, Lev E, Wysocki R (2018) The influence of topographic roughness on lava flow emplacement. *Bull*

566 *Volcanol* 80:. <https://doi.org/10.1007/s00445-018-1238-9>

567 Rust AC, Cashman KV (2011) Permeability controls on expansion and size distributions of pyroclasts. *J Geophys*

568 *Res Solid Earth* 116(B11). <https://doi.org/10.1029/2011JB008494>

569 Rust AC, Cashman KV (2004) Permeability of vesicular silicic magma: inertial and hysteresis effects. *Earth Planet*

570 *Scie Lett* 228(1-2):93–107. <https://doi.org/10.1016/j.epsl.2004.09.025>

571 Salvatore V, Cigala V, Taddeucci J, et al (2020) Gas-Pyroclast Motions in Volcanic Conduits During Strombolian

572 Eruptions, in *Light of Shock Tube Experiments*. *J Geophys Res Solid Earth* 125:.

573 <https://doi.org/10.1029/2019JB019182>

574 Saxby J, Beckett F, Cashman K, et al (2018) The impact of particle shape on fall velocity: Implications for volcanic

575 ash dispersion modelling. *J Volcanol Geotherm Res* 362:32–48.

576 <https://doi.org/10.1016/j.jvolgeores.2018.08.006>

577 Schepp LL, Ahrens B, Balcewicz M, et al (2020) Digital rock physics and laboratory considerations on a high-

578 porosity volcanic rock. 1–16. <https://doi.org/10.1038/s41598-020-62741-1>

579 Schmid M, Kueppers U, Cigala V, et al (2020) Release characteristics of overpressurised gas from complex vents:

580 implications for volcanic hazards. *Bull Volcanol* 82(11):1–12. <https://doi.org/10.1007/s00445-020-01407-2>

581 Schmiedel T, Galland O, Haug T, et al (2019) Coulomb failure of Earth's brittle crust controls growth, emplacement

582 and shapes of igneous sills, saucer-shaped sills and laccoliths. *Earth Planet Sci Lett* 510:161–172.

583 <https://doi.org/10.1016/j.epsl.2019.01.011>

584 Seropian G, Stix J (2018) Monitoring and forecasting fault development at actively forming calderas: An

585 experimental study. *Geology* 46:23–26. <https://doi.org/10.1130/G39551.1>

586 Seyfried R, Freundt A (2000) Experiments on conduit flow and eruption behavior of basaltic volcanic eruptions. *J*

587 *Geophys Res Solid Earth* 105:23727–23740. <https://doi.org/10.1029/2000jb900096>

588 Sher D, Woods AW (2017) Experiments on mixing in pyroclastic density currents generated from short-lived

589 volcanic explosions. *Earth Planet Sci Lett* 467:138–148. <https://doi.org/10.1016/j.epsl.2017.03.009>

590 Smith G, Rowley P, Williams R, et al (2020) A bedform phase diagram for dense granular currents. *Nat Commun*

591 11(1):2873. <https://doi.org/10.1038/s41467-020-16657-z>

592 Soldati A, Farrell JA, Wysocki R, Karson JA (2021) Imagining and constraining ferrovulcanic eruptions and

593 landscapes through large-scale experiments. *Nat Comm* 12:1711. <https://doi.org/10.1038/s41467-021-21582-w>

594

595 Sonder I, Graettinger AH, Valentine GA (2015) Scaling multiblast craters: General approach and application to

596 volcanic craters. *J Geophys Res Solid Earth* 120(9):6141–58. <https://doi.org/10.1002/2015JB012018>

597 Sonder I, Harp A, Graettinger AH, et al (2018). Meter-scale experiments on magma-water interaction. *J Geophys*

598 *Res Solid Earth* 123:10,597–10,615. <https://doi.org/10.1029/2018JB015682>

599 Soule SA, Cashman K V. (2004) The mechanical properties of solidified polyethylene glycol 600, an analog for lava  
600 crust. *J Volcanol Geotherm Res* 129:139–153. [https://doi.org/10.1016/S0377-0273\(03\)00237-3](https://doi.org/10.1016/S0377-0273(03)00237-3)

601 Spina L, Cimarelli C, Scheu B, et al (2016) On the slow decompressive response of volatile- and crystal-bearing  
602 magmas: An analogue experimental investigation. *Earth Planet Sci Lett* 433:44–53.  
603 <https://doi.org/10.1016/j.epsl.2015.10.029>

604 Stevenson RJ, Bagdassarov NS, Dingwell DB, Romano C (1998) The influence of trace amounts of water on the  
605 viscosity of rhyolites. *Bull Volcanol* 60(2):89-97. <https://doi.org/10.1007/s004450050218>

606 Sulpizio R, Castioni D, Rodriguez-Sedano LA, et al (2016) The influence of slope-angle ratio on the dynamics of  
607 granular flows: insights from laboratory experiments. *Bull Volcanol* 78(11):77. [https://doi:10.1007/s00445-](https://doi:10.1007/s00445-016-1069-5)  
608 [016-1069-5.](https://doi:10.1007/s00445-016-1069-5)

609 Taddeucci J, Alatorre-Ibarguengoitia MA, Palladino DM, et al (2015) High-speed imaging of Strombolian  
610 eruptions: Gas-pyroclast dynamics in initial volcanic jets. *Geophys Res Lett* 42:6253–6260.  
611 <https://doi.org/10.1002/2015GL064874>

612 Taisne B, Jaupart C (2009) Dike propagation through layered rocks. *J Geophys Res Solid Earth* 114(B9).  
613 <https://doi.org/10.1029/2008JB006228>

614 Taisne B, Tait S (2009) Eruption versus intrusion? arrest of propagation of constant volume, buoyant, liquid-filled  
615 cracks in an elastic, brittle host. *J Geophys Res Solid Earth* 114:1–7. <https://doi.org/10.1029/2009JB006297>

616 Taisne B, Tait S (2011) Effect of solidification on a propagating dike. *J Geophys Res Solid Earth* 116:1–14.  
617 <https://doi.org/10.1029/2009JB007058>

618 Touvet T, Balmforth NJ, Craster R V, Sutherland BR (2011) Fingering instability in buoyancy-driven fluid-filled  
619 cracks. *J Fluid Mech* 672:60–77. <https://doi.org/10.1017/S0022112010005860>

620 Valentine GA (2020) Initiation of dilute and concentrated pyroclastic currents from collapsing mixtures and origin  
621 of their proximal deposits. *Bull Volcanol* 82:20. <https://doi.org/10.1007/s00445-020-1366-x>

622 Valentine GA, Graettinger AH, Macorps É, et al (2015) Experiments with vertically and laterally migrating  
623 subsurface explosions with applications to the geology of phreatomagmatic and hydrothermal explosion  
624 craters and diatremes. *Bull Volcanol* 77(3):1-7. <https://doi.org/10.1007/s00445-015-0901-7>

625 Van Eaton AR, Amigo Á, Bertin D, et al (2016) Volcanic lightning and plume behavior reveal evolving hazards  
626 during the April 2015 eruption of Calbuco volcano, Chile. *Geophys Res Lett* 43:3563– 3571.  
627 <https://doi.org/10.1002/2016GL068076>

628 Wadge G, Voight B, Sparks RSJ et al (2014) An overview of the eruption of Soufriere Hills Volcano, Montserrat  
629 from 2000 to 2010. *Mem Geol Soc London* 39:1–40. <https://doi.org/10.1144/M39.1>

630 Watson LM (2020) Using unsupervised machine learning to identify changes in eruptive behavior at Mount Etna,  
631 Italy. *J Volcanol Geotherm Res* 405, 107042. <https://doi.org/10.1016/j.jvolgeores.2020.107042>

632 Weit A, Roche O, Dubois T, Manga M (2018) Experimental Measurement of the Solid Particle Concentration in  
633 Geophysical Turbulent Gas-Particle Mixtures. *J Geophys Res Solid Earth*, 123(5):3747-3761.  
634 <https://doi.org/10.1029/2018JB015530>

635 Witham F, Woods AW, Gladstone C (2006) An analogue experimental model of depth fluctuations in lava lakes.  
636 *Bull Volcanol* 69:51–56. <https://doi.org/10.1007/s00445-006-0055-8>

637 Zhu J, Liu X, Shi Q, et al (2020) Development trends and perspectives of future sensors and MEMS/NEMS.  
638 *Micromachines* 11:. <https://doi.org/10.3390/mi11010007>

639 Zorn EU, Walter TR, Heap MJ, Kueppers U (2020) Insights into lava dome and spine extrusion using analogue  
640 sandbox experiments. *Earth Planet Sci Lett* 551:116571. <https://doi.org/10.1016/j.epsl.2020.116571>

641

642

**Table 1** Key parameter ranges for analog experiments versus their natural counterparts

	Parameter [Units]	Physical description	Experiments	Nature	References
<b>Magma intrusion</b>	$h$ [m]	overburden height	0.06 – 0.10	$10^1 - 10^4$	Mathieu et al., 2008; Galland et al., 2014; Poppe et al., 2019
	$B$ [m]	dike transverse breadth	< 0.4	$10^2 - 10^4$	Kavanagh et al. 2018a, b; Pansino et al. 2019a, b
	$C$ [kg m <sup>-1</sup> s <sup>-2</sup> ]	solid cohesion	1 – 700	$10^5 - 10^7$	Galland et al. 2006, 2014; Abdelmalak et al. 2016; Schmiedel et al. 2019; Poppe et al. 2019, 2021
	$E$ [kg m <sup>-1</sup> s <sup>-2</sup> ]	Young's modulus	$10^3 - 10^4$	$30 \times 10^9$	Kavanagh et al. 2013; Pansino & Taisne 2019
	$G$ [kg m <sup>-1</sup> s <sup>-2</sup> ]	shear modulus	$10^3 - 10^4$	$30 \times 10^9$	Rivalta et al. 2005
	$H$ [m]	dike thickness	$10^{-3} - 10^{-2}$	$10^{-2} - 10$	Pansino et al. 2019a, b
	$K_c$ [kg m <sup>-0.5</sup> s <sup>-2</sup> ]	critical fracture toughness	40 – 170	$10^6$	Meredith & Atkinson 1985; Kavanagh et al. 2013
	$L$ [m]	dike axial length	< 0.4	$10^2 - 10^4$	Kavanagh et al. 2018a, b; Pansino et al. 2019a, b
	$Q$ [m <sup>3</sup> s <sup>-1</sup> ]	volumetric flow rate	$10^{-8} - 10^{-5}$	$10^{-2} - 10^2$	Pansino et al. 2019a, b
	$T$ [°C]	temperature	30 – 70	700 – 1400	Taisne & Tait 2011; Pansino et al. 2019a, b
	$T_0$	solid tensile strength	5 – 200	$10^5 - 10^7$	Abdelmalak et al., 2016; Poppe et al., 2021
	$\alpha$ [m <sup>2</sup> s <sup>-1</sup> ]	thermal diffusivity	$10^{-7} \dagger$	$10^{-7} - 10^{-6}$	Hartlieb et al. 2016; Pansino et al. 2019a, b
	$\rho_s$ [kg m <sup>-3</sup> ]	solid crust density	1000 – 1050	1600 – 3000	Gailler et al. 2009; Kavanagh et al. 2013; Guldstrand et al. 2017
	$\rho_l$ [kg m <sup>-3</sup> ]	liquid magma density	~ 0 – 1440	~ 40 – 2700	Rivalta et al. 2005; Galland et al. 2006; Mathieu et al. 2008; Taisne & Tait 2009; Schepp et al. 2020
	$\Delta\rho$ [kg m <sup>-3</sup> ]	crust-fluid density contrast	370 – 1000	400 – 3000	Rivalta et al. 2005; Taisne & Jaupart 2009
	$\gamma$ [kg s <sup>-2</sup> ]	surface energy	1	1	Kavanagh et al. 2013
	$\mu$ [kg m <sup>-1</sup> s <sup>-1</sup> ]	fluid dynamic viscosity	$10^{-5} - 10^{-1}$	$1 - 10^{12} \ddagger$	Rivalta et al. 2005; Gonnerman 2015; Kavanagh et al. 2018a, b; Pansino & Taisne 2019
	$\phi$ [degrees]	solid internal friction angle	21 – 35	25 – 45	Galland et al. 2006; Galland et al. 2014; Abdelmalak et al. 2016; Schmiedel et al. 2019; Poppe et al. 2019, 2021
	$\nu$	Poisson's ratio	0.5	0.25	Rivalta et al. 2005
	A/C	activation/cooling time ratio	0.2	0.1 – 0.2	Derrien and Taisne 2019
L*	dimensionless length	< 10	$10^{-1} - 10^2$	Taisne & Tait 2009	
Re	Reynolds number	< $10^2$	10	Lister & Kerr 1991; Touvet et al. 2011; Galland et al. 2014	
$\Theta$	dimensionless temperature	0.76 – 1	0.9 – 0.95	Taisne & Tait 2011; Pansino et al. 2019a, b	
$\Phi$	dimensionless thermal flux	$10^{-2} - 10$	$10^{-3} - 10^2$	Taisne & Tait 2011; Pansino et al. 2019a, b	

<sup>†</sup>gelatin<sup>‡</sup>gas-poor/rich



**Table 1:** Continued

	Parameter [Units]	Physical description	Experiments	Nature	References
<b>Gravitational deformation (chronic)</b>	$g$ [ $\text{m s}^{-2}$ ]	gravitational acceleration	9.81	3.70 (Mercury) 8.87 (Venus) 9.81 (Earth) 3.69 (Mars)	Merle & Borgia 1996; Delcamp et al. 2008; Kervyn et al. 2010; Byrne et al. 2013
	$B$ [m]	brittle layer thickness	$10^{-2} - 10^{-1}$	$10^3 - 10^5$	Merle & Borgia 1996; Delcamp et al. 2008; Kervyn et al. 2010; Byrne et al. 2013
	$D$ [m]	ductile layer thickness	$10^{-1}$	$10^3 - 10^5$	Merle & Borgia 1996; Delcamp et al. 2008; Kervyn et al. 2010; Byrne et al. 2013
	$E$ [Pa]	Young's modulus	$5 \times 10^6$	$7.5 \times 10^{10}$	Merle & Borgia 1996; Delcamp et al. 2008; Kervyn et al. 2010; Byrne et al. 2013
	$H$ [m]	Cone height	$10^{-2}$	$10^3 - 10^5$	Merle & Borgia 1996; Delcamp et al. 2008; Kervyn et al. 2010; Byrne et al. 2013
	$P$ [m]	decollement thickness	$10^{-4}$	$1 - 10^3$	Byrne et al. 2013
	$Q$ [m]	decollement depth	$10^{-3}$	$0 - 10^3$	Byrne et al. 2013
	$R$ [m]	cone radius	$10^{-1}$	$10^3 - 10^5$	Merle & Borgia 1996; Delcamp et al. 2008; Kervyn et al. 2010; Byrne et al. 2013
	$S$ [ $\text{m s}^{-1}$ ]	velocity of deformation	$10^{-6} - 10^{-5}$	$10^{-12} - 10^{-10}$	Merle & Borgia 1996; Delcamp et al. 2008; Kervyn et al. 2010; Byrne et al. 2013
	$T$ [s]	time span of spreading	$3 \times 10^5$	$10^{12} - 10^{13}$	Kervyn et al. 2010
	$T_0$ [Pa]	brittle cohesion	$10^2$	$10^6 - 10^8$	Merle & Borgia 1996; Delcamp et al. 2008; Kervyn et al. 2010; Byrne et al. 2013
	$\mu$ [Pa s]	ductile material viscosity	$10^3 - 10^4$	$10^{20} - 10^{22}$	Merle & Borgia 1996; Delcamp et al. 2008; Kervyn et al. 2010; Byrne et al. 2013
	$\rho_b$ [ $\text{kg m}^{-3}$ ]	brittle material density	$10^3 - 10^4$	$10^3 - 10^5$	Merle & Borgia 1996; Delcamp et al. 2008; Kervyn et al. 2010; Byrne et al. 2013
	$\rho_d$ [ $\text{kg m}^{-3}$ ]	ductile material density	$10^3$	$3.3 - 3.5 \times 10^3$	Merle & Borgia 1996; Delcamp et al. 2008; Kervyn et al. 2010; Byrne et al. 2013
	$\nu$	Poisson's ratio	0.2	0.3	Merle & Borgia 1996; Delcamp et al. 2008; Kervyn et al. 2010; Byrne et al. 2013
	$\Theta$	brittle friction coefficient	0.63	0.65	Merle & Borgia 1996; Delcamp et al. 2008; Kervyn et al. 2010; Byrne et al. 2013

**Table 1:** Continued

	Parameter [Units]	Physical description	Experiments	Nature	References
<b>Caldera faulting</b>	$C_m$ [Pa]	brittle cohesion	$0 - 3 \times 10^2$	$10^5 - 10^8$	Holohan et al. 2008; Ruch et al. 2012; Poppe et al. 2015
	$G_r$ [ $\text{km}^3 \text{ka}^{-1}$ ]	cone growth rate	$10^{-11}$	$10^{-2} - 10$	Grosse et al. 2020
	$L$ [m]	length	$10^{-2} - 10^{-1}$	$10^{-2} - 10^4$	Roche et al. 2000; Holohan et al. 2008; Ruch et al. 2012; Poppe et al. 2015
	$T_{mr}$ [s]	chamber residence time	$10^3 - 10^4$	$10^{12} - 10^{14}$	Holohan et al. 2008
	$V_{mc}$ [ $\text{m s}^{-1}$ ]	caldera collapse velocity	$10^{-7} - 10^{-6}$	$10^{-2} - 10^{-1}$	Holohan et al., 2008; Ruch et al., 2012; Poppe et al., 2015
	$V_{mr}$ [ $\text{m s}^{-1}$ ]	strike-slip velocity	$10^{-6} - 10^{-4}$	$10^{-10} - 10^{-8}$	Holohan et al., 2008; Grosse et al. 2020
	$\mu_m$ [Pa s]	magma viscosity	$50 - 10^4$	$10^4 - 10^{12}$	Roche et al. 2000; Holohan et al. 2008; Ruch et al. 2012; Poppe et al. 2015
	$\phi_m$ [ $^\circ$ ]	angle of internal friction	22 – 37	30 – 45	Roche et al. 2000; Holohan et al. 2008; Ruch et al. 2012; Poppe et al. 2015
	$\rho_m$ [ $\text{kg m}^{-3}$ ]	brittle material density	1400	2600 – 3000	Roche et al. 2000; Holohan et al. 2008; Ruch et al. 2012; Poppe et al. 2015
<b>Domes and lava flows</b>	$C_p$ [ $\text{J kg}^{-1} \text{K}^{-1}$ ]	heat capacity	1200	1200	Rumpf et al. 2018
	$R_H$ [m]	resurgent dome height	$10^{-2}$	$1 - 10^3$	Brothelande et al. 2016
	$R_L$ [m]	resurgent dome length	$3 \times 10^{-1}$	$10^3 - 10^4$	Brothelande et al. 2016
	$R_W$ [m]	resurgent dome width	$10^{-1}$	$10^3 - 10^4$	Brothelande et al. 2016
	$T$ [ $^\circ\text{C}$ ]	temperature	900 – 1473	700 – 1600	Griffiths 2000; Rumpf et al. 2018 and references therein; Sonder et al. 2018; Soldati et al. 2021
	$\alpha$ [ $\text{m}^2 \text{s}^{-1}$ ]	thermal diffusivity	$10^{-7} - 10^{-6}$	$10^{-7} - 10^{-6}$	Romine et al. 2012; Rumpf et al. 2018
	$\rho$ [ $\text{kg m}^3$ ]	density	890 – 2700	900 – 2500	Kavanagh et al. 2018a, b; Rumpf et al. 2018; Sonder et al. 2018
	$\mu$ [Pa s]	dynamic viscosity	$10^{-5} - 10^{14}$	$10 - 10^{11}$	Huppert et al. 1982; Stevenson et al. 1998; Kavanagh et al. 2018a, b; Rumpf et al. 2018; Sonder et al. 2018
	$\Phi_g$	gas volume fraction	0.10 – 0.80	0 – 0.95	Rust and Cashman 2004, 2011; Oppenheimer et al. 2015; Gonnerman 2015; Gonnerman et al. 2017; Fauria and Manga 2018
	$\Psi$	flow regime parameter	2.24 – 2060	33 – 118	Fink and Griffiths 1990; Gregg and Fink 2000; Rumpf et al. 2018
	Pe	Péclet number	$10^4 - 10^5$	$10^2 - 10^8$	Griffiths 2000; Rumpf et al. 2018
Re	Reynolds number	$7.4 \times 10^{-3} - 24$	$10^{-10} - 10^6$	Huppert et al. 1984; Huppert and Sparks 1985; Griffiths 2000; Rumpf et al. 2018	

**Table 1:** Continued

	Parameter [Units]	Physical description	Experiments	Nature	References
<b>Cratering</b>	$d$ [m]	depth of explosion	0 – 1	$10 - 10^2$	Graettinger et al. 2014; Sonder et al. 2015
	$d_p$ [m]	particle diameter	0.1 – 5	$10^{-2} - 10^3$	Graettinger et al. 2014; Graettinger and Valentine 2017
	$h$ [m]	jet height	0.1 – 20	$10 - 10^3$	Graettinger et al. 2014; Ort et al. 2018
	$kg$ [kg]	mass of ejecta	$10^2 - 10^3$	$10^2 - 10^8$	Ripepe et al. 1993; Kilgour et al. 2010; Graettinger et al. 2014; Lube et al. 2014
	$m$ [m]	max ballistic ejecta distance	0.5 – 50	$10 - 10^3$	Graettinger et al. 2014; Ort et al. 2018
	$t_{pulse}$ [seconds]	eruption explosion interval	$10^{-3} - 10^4$	$> 10^{-1}$	Dürig et al. 2015; Graettinger et al. 2018; Neilsen et al. 2019; Gilchrist et al. 2020; Rowell et al. 2020
	$d_c$ [m]	crater depth	(-0.1)–(-0.5)	$10 - 10^2$	Sonder et al. 2015; Graettinger 2018
	$D_{sc}$ [m J <sup>-1/3</sup> ]	scaled depth	$10^{-3} - 10^{-2}$	$10^{-3} - 10^{-2}$	Sonder et al. 2015; Valentine et al. 2015
	$E$ [J]	explosion energy	$10^5 - 10^7$	$10^9 - 10^{15}$	Graettinger et al. 2014; Sonder et al. 2015
	$W_c$ [m]	crater diameter	0.3 – 6	$10 - 10^3$	Graettinger et al. 2014; Sonder et al. 2015
<b>Volcanic jets and plumes</b>	$d_p$ [m]	particle diameter	$10^{-5} - 10^{-3}$	$10^{-6} - 10^{-2}$	Dellino et al. 2010; Carazzo & Jellinek 2012
	$f_{ftm}$ [s <sup>-1</sup> ]	fountain frequency	$10^{-2} - 10^{-1}$	$10^{-4} - 1$	Gilchrist & Jellinek 2021
	$r_0$ [m]	source radius	$10^{-3} - 1$	$10 - 10^2$	Dellino et al. 2010; Carazzo & Jellinek 2012
	$t_{pulse}$ [seconds]	eruption explosion interval	$10^{-2} - 10^2$	$> 10^{-1}$	Dürig et al. 2015; Gilchrist et al. 2020; Rowell et al. 2020
	$u_0$ [m/s]	source speed	$10^{-3} - 10^3$	$10 - 10^3$	Kieffer and Sturtevant 1984; Dellino et al. 2010; Carazzo & Jellinek 2012; Gilchrist & Jellinek 2021
	$u_p$ [m/s]	particle settling speed	0.1 – 1	$10^{-1} - 10^2$	Carazzo & Jellinek 2012; Saxby et al. 2018; Gilchrist & Jellinek 2021
	$H_{ftm}$ [m]	fountain/jet height	0.1	$10^3 - 10^4$	Gilchrist & Jellinek 2021
	$H_{pl}$ [m]	plume height	0.1	$10^3 - 10^4$	Gilchrist & Jellinek 2021
	$H_{OS}$ [m]	overshoot height	$10^{-2} - 10^{-1}$	$10^3 - 10^4$	Gilchrist & Jellinek 2021
	$N$ [s <sup>-1</sup> ]	buoyancy frequency	$10^{-1}$	$10^{-2}$	Carazzo & Jellinek 2012
	$\mu$ [kg m <sup>-1</sup> s <sup>-1</sup> ]	fluid dynamic viscosity	$10^{-3}$	$10^{-5}$	Carazzo & Jellinek 2012
	$\rho_a$ [kg m <sup>-3</sup> ]	ambient fluid density	998 – 1040	$10^{-3} - 1$	Carazzo & Jellinek 2012; Gilchrist and Jellinek 2021
	$\rho_f$ [kg m <sup>-3</sup> ]	interstitial fluid density	998 – 1050	0.1 – 1	Carazzo & Jellinek 2012; Gilchrist and Jellinek 2021
	$\rho_s$ [kg m <sup>-3</sup> ]	solid (particle) density	42 – 3210	750 – 2500	Carey et al. 1988; Carazzo & Jellinek 2012; Carazzo et al. 2015; Gilchrist and Jellinek 2021
	$\phi_0$	particle volume fraction	$10^{-3} - 10^{-2}$	$10^{-4} - 10^{-1}$	Carazzo & Jellinek 2012; Jessop et al. 2016; Gilchrist & Jellinek 2021
	$e$	restitution coefficient	0 – 0.85	0 – 0.85	Cagnoli and Manga 2003; Dufek et al. 2009
	Ma	source Mach number	< 3.8	< 1.7	Kieffer and Sturtevant 1984; Orescanin et al. 2014; Schmid et al. 2020

**Table 1:** Continued

	Parameter [Units]	Physical description	Experiments	Nature	References
	$Re_0$	source Reynolds number	3000 – 12000	$10^7 - 10^9$	Carazzo & Jellinek 2012
	$Re_p$	particle Reynolds number	1.3 – 6.5	$10^{-4} - 10^6$	Carazzo & Jellinek 2012; Gilchrist and Jellinek 2021
	$Ri_0$	source Richardson number	$10^{-7} - 1$	$10^{-3} - 10$	Carazzo & Jellinek 2012; Carazzo et al. 2014; Carazzo et al. 2015; Jessop et al. 2016; Gilchrist and Jellinek 2021
	$St_0$	source Stokes number	0.2 – 6.0	$10^{-2} - 10^2$	Carazzo & Jellinek 2012; Jessop et al. 2016; Gilchrist & Jellinek 2021
	$\Sigma_0$	source stability number	$10^{-3} - 10^{-2}$	$10^{-3} - 1$	Carazzo & Jellinek 2012; Jessop et al. 2016; Gilchrist & Jellinek 2021
<b>Pyroclastic density currents</b>	$d_p$ [m]	particle diameter	$10^{-6} - 10^{-2}$	$10^{-6} - 1$	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	$u$ [ $m s^{-1}$ ]	bulk speed	0.1 – 10	5 – 200	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	$H$ [m]	flow height	0.01 – 5	10 – 1000	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	KE [ $J m^{-3}$ ]	kinetic energy density	$10^{-2} - 10^3$	$10^{-2} - 10^4$	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	TEb [ $J m^{-3}$ ]	buoyant thermal energy	$10^1 - 10^3$	$10^3 - 10^4$	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	$\mu$ [ $kg m^{-1} s^{-1}$ ]	interstitial fluid dynamic viscosity	$1.8 - 4 \times 10^{-5}$	$1.8 - 3.5 \times 10^{-5}$	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	$\mu_{pp}$	internal friction coefficient	26 – 40	35 – 40	Roche et al. 2012; Lube et al. 2015
	$\mu_b$ [degrees]	basal friction coefficient	35 – 40	35 – 40	Lube et al. 2015
	$\rho_a$ [ $kg m^{-3}$ ]	ambient fluid density	1.2 – 1.3	1.1 – 1.3	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	$\rho_f$ [ $kg m^{-3}$ ]	interstitial fluid density	0.6 – 1.2	0.6 – 1.2	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	$\rho_s$ [ $kg m^{-3}$ ]	solid density	350 – 2900	350 – 2900	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	$e$	restitution coefficient	0 – 0.85	0 – 0.85	Cagnoli and Manga 2003; Dufek et al. 2009
	C	source particle concentration	$10^{-5} - 0.7$	$10^{-5} - 0.7$	Andrews and Manga, 2012; Lube et al. 2015;
	Fr	densimetric Froude number	0.5 – 5	0.5 – 5	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	I	inertial number	$10^{-6} - 10$	$10^{-6} - 10$	Breard et al. 2020
N	pore pressure	0 – > 1	0 – > 1	Druitt et al. 2007; Roche 2012; Breard et al. 2019	

**Table 1:** Continued

	<b>Parameter [Units]</b>	<b>Physical description</b>	<b>Experiments</b>	<b>Nature</b>	<b>References</b>
	Re	Reynolds number	$10^1$ - $10^3$	$10^6$ - $10^{10}$	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	Ri	Richardson number	0.01 – 10	0 – 10	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	Ri <sub>t</sub>	thermal Richardson number	0.02 – 4.5	0 – 5	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	Pn	Rouse number	0.7 – 10	$10^{-3}$ - $10^{-1}$	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	Ψ	grain sphericity	0.4 – 1	0.4 – 1	Dellino et al. 2005
	Σ	stability number	$10^{-2}$ -10	$10^{-6}$ - $10^5$	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	St	Stokes number	$10^{-6}$ -10	$10^{-6}$ -10	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
	Str	Strouhal number	0.3	0.3	Dellino et al. 2007; Andrews & Manga, 2012; Roche, 2012; Lube et al. 2015; Brosch & Lube 2019
<b>Debris flows</b>	$d_p$ [m]	particle diameter	$10^{-6} - 10^{-1}$	$10^{-6} - 1$	Iverson et al. 2010; Iverson 2012
	$k$ [m <sup>2</sup> ]	hydraulic permeability	$10^{-12} - 5 \times 10^{-10}$	$10^{-13} - 10^{-10}$	Iverson et al. 2010; Iverson 2012
	$u$ [m s <sup>-1</sup> ]	bulk speed	1 – 10	1 – 50	Iverson et al. 2010; Iverson 2012
	$D$ [m <sup>2</sup> ]	hydraulic diffusivity	$1 - 5 \times 10^{-2}$	$10^{-2}$	Iverson et al. 2010; Iverson 2012
	$H$ [m]	flow height	0.1 – 1	0.1 – 100	Iverson et al. 2010; Iverson 2012
	$\rho_s$ [kg m <sup>-3</sup> ]	solid density	2000 – 2500	350 – 2900	Iverson et al. 2010; Iverson 2012
	$\rho_f$ [kg m <sup>-3</sup> ]	interstitial fluid density	2000 – 2500	350 – 2900	Iverson et al. 2010; Iverson 2012
	$\mu$ [kg m <sup>-1</sup> s <sup>-1</sup> ]	interstitial fluid dynamic viscosity	$10^{-3} - 10^{-1}$	$10^{-3} - 10^{-1}$	Iverson et al. 2010; Iverson 2012
	$\mu_b$ [degrees]	basal friction coefficient	39 – 40	~ 40	Iverson et al. 2010; Iverson 2012
	$\mu_{pp}$ [degrees]	internal friction coefficient	~ 39	~ 40	Iverson et al. 2010; Iverson 2012
	$N_p$	pore pressure number	$10^{-4} - 10^{-3}$	$10^{-8} - 10^{-6}$	Iverson et al. 2010; Iverson 2012