The lifecycle of volcanic ash: advances and ongoing challenges

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Abstract
Explosive volcanic eruptions can produce vast amounts of volcanic ash made up mainly of fragments of magmatic glass, country rock and minerals < 2 mm in size. Ash particles forming from magma fragmentation are generated by several processes when brittle response accommodates (local) deformation stress that exceeds the capability of the bulk material to respond by viscous flow. These processes span a wide range of temperatures, can occur inside or outside the volcanic edifice and can involve all melt compositions. Ash is then dispersed by volcanic and atmospheric processes over large distances and can have global distributions. Explosive eruptions have repeatedly drawn focus to studying volcanic ash. The continued occurrence of such eruptions worldwide and their widespread impacts motivates the study of the chemical and physical processes involved in the lifecycle of volcanic ash (e.g. magma fragmentation, particle aggregation), as well as the immediate to long-term effects (e.g. water and air pollution, soil fertilization) and consequences (e.g. environmental, economic, social) associated with ashfall. In this perspectives article, we reflect on the progress made over the last two decades in understanding (1) volcanic ash generation; (2) dispersion, sedimentation and erosion; and (3) impacts on the atmosphere, hydrosphere, biosphere and modern infrastructure. Finally, we discuss open questions and future challenges.

Keywords Tephra · Explosive eruptions · Ash fallout · Volcanic ash impacts

Introduction
Commonly, scientific progress goes hand-in-hand with technological advances. Alternatively, events with significant societal impacts may cause a temporal shift in focus and draw the attention of researchers, government institutions and funding agencies. Volcanology, and its subfield of volcanic ash studies, is no exception. The first detailed efforts to better understand processes leading to explosive volcanic eruptions trace back to the 1970s (McBirney and Murase 1970; Sparks 1978). However, it was not until the 1980 explosive eruption of Mt. St. Helens (USA) that volcanic ash studies gained momentum. During this event, (i) ash dispersal was monitored in real-time, allowing for immediate correlation with the impact on the environment, people and infrastructure (Blong 1984; Miller and Hoblitt 1981); (ii) satellite images were used to track the motion of volcanic clouds and retrieve data on its ascent and radial expansion (Sparks et al. 1986; Holasek and Self 1995); and (iii) models on ash transport and deposition were developed (Carey and Sparks 1986; Harris et al. 1981). The 1990s were then marked by the emergence of experimental volcanology, providing new insights into explosive eruptions and ash generation processes (Mader et al. 1994; Alidibirov and Dingwell 1996).

In the early 2000s, ash-related studies benefited from the sophistication of computational capacities, analytical techniques and remote sensing technologies (Ersoy et al. 2006; Shea et al. 2009). Despite the progress achieved up to this point, the relatively small (VEI 3) eruption of Eyjafjallajökull in Iceland in April 2010 exposed the vulnerability of modern societies and the need for additional efforts to face the challenge of understanding and mitigating the impact of volcanic ash on the environment and society.
Here, we summarize key aspects of ash-related research since 2000 CE based on its lifecycle through (i) ash generation processes; (ii) dispersion, sedimentation and erosion; and (iii) impact of volcanic ash on the atmosphere, hydrosphere, biosphere and infrastructure. Finally, we look into the next decade (the 2020s) for prospective research directions and challenges.

**Volcanic ash generation**

Volcanic ash comprises fragments of magmatic glass, country rock and minerals of <2 mm in diameter that are emitted during explosive volcanic events. Magma fragmentation is the fundamental mechanism behind ash generation and it results from a transition between a melt with dispersed gas bubbles (± crystals) to a continuous gas phase with suspended magma fragments (pyroclasts) (Fig. 1). During the ’90s, several mechanisms and criteria were proposed to explain the brittle failure of magma, such as the strain-induced by magma acceleration as well as volatile expansion due to decompression with ascent (e.g. Mader et al. 1994; Dingwell 1996; Papale 1999).

Post-2000, characterization of ash particles has provided key information on the state of magma before fragmentation (Lloyd et al. 2013). Microtextural analysis of volcanic ash (i.e. vesicularity, componentry, crystallinity degree, shape; e.g. Wright et al. 2012; Cassidy et al. 2015; Matsumoto and Geshi 2021), along with grain size analyses and decompression and fragmentation experiments (e.g. Kueppers et al. 2006; Paredes-Mariño et al. 2017; Forte and Castro 2019), has proven helpful in constraining the complex dynamics of magma ascent and fragmentation, as well as in estimating decompression rates and fragmentation efficiency. Volcanic ash also holds information about eruptive style transitions, as shown by textural, morphological and chemical studies (e.g. Ersoy et al. 2006; Castro et al. 2014; Liu et al. 2017). However, volcanic ash is the lowest end member of a wide spectrum of particle sizes; therefore, to fully understand eruptive processes and fragmentation mechanisms, the integration of the physical, chemical and textural properties of lapilli and blocks is also important (e.g. Eyenchene and Le Pennec 2012; Pioli and Harris 2019; Trafton and Giachetti 2021).

There is general consensus that volcanic ash is also generated during secondary processes above the fragmentation level (Fig. 1), i.e., (i) within the conduit, (ii) in volcanic plumes or (iii) during transport in pyroclastic density currents (e.g. Dufek and Manga 2008; Jones et al. 2016; Paredes-Mariño et al. 2019) and (iv) by break-up during sedimentation (Mueller et al. 2017). Secondary fragmentation leads to particle size reduction and shape alteration due to mechanical interactions of variable energy (Jones and Russell 2017; Hornby et al. 2020).
**Volcanic ash dispersion, sedimentation and erosion**

Explosive eruptions inject large quantities of gas and ash particles of different sizes, shapes and chemistries into the atmosphere. Given the small size and high surface area of very fine ash (<30 µm), such particles have the potential to be transported hundreds to thousands of kilometres away from the source (Rose and Durant 2009). The past two decades have witnessed significant improvements in our capacity of measuring (Flentje et al. 2010; Guehenneux et al. 2015) and modelling ash transport and deposition (Costa et al. 2006; Bonadonna et al. 2012) over such spatial scales. The development of increasingly high-resolution cameras—and even the extended use of smartphones—has provided ample and high-quality footage of eruption plumes, further supporting the study of eruption dynamics (Schipper et al. 2013; Giordano and De Astis 2021), volcanic plume evolution (Mastin 2014; Tournigand et al. 2017) and lightning discharges (e.g. Aizawa et al. 2016; Cimarelli et al. 2016; Behnke et al. 2018).

In addition to the local wind field, the ascent of a volcanic plume, as well as the dispersion and deposition of tephra, plus their sedimentation rate, depends on air entrainment and the physical characteristics of the ejected volcanic pyroclasts (Folch et al. 2016). In this regard, the use of shape descriptors instead of a spherical approximation for ash particles shape has, for example, been encouraged to increase the accuracy of calculated volcanic ash sedimentation rates (Saxby et al. 2020a). Additionally, scanning electron microscopy, stereoscopic imaging and micro-computed tomography techniques have proved valuable in estimating the surface area of the irregular shapes of volcanic ash (Ersoy et al. 2010; Umo et al. 2021). At the same time, experimental studies have constrained boundary conditions for ash aggregation (Van Eaton et al. 2012; Mueller et al. 2016; Fig. 1), a process that is known to affect fallout patterns and dispersal dynamics (Taddeucci et al. 2011; Poret et al. 2017). However, it has also been recognized that this is a reversible process as mechanical forces, or evaporation, can cause partial disintegration of aggregates (Bonadonna et al. 2011).

The use of satellite-based instruments and images, as well as ground-based video obtained in the visible and infrared range, has been shown to allow the constraint of the evolution of plumes, while also allowing source conditions to be derived (e.g. Pardini et al. 2017; Tournigand et al. 2017; Poret et al. 2018). Such measurements are important in identifying temporal changes in eruption intensity or style (Harris and Ripepe 2007; Lopez et al. 2015). Furthermore, these advances in satellite and ground-based remote sensing have improved the ability to forecast the potential impact of volcanic clouds on airspace so as to promote the development of strategies for determining volcanic ash presence in the atmosphere (Dacre et al. 2011; Pavolonis et al. 2018).

Since 2000 tephra stratigraphy mapping of recent volcanic events has also benefited from improved remote sensing technologies and the expansion of volcano monitoring networks, making it possible to relate event dynamics (i.e. dispersion, sedimentation and timing) with the associated deposits (Alfano et al. 2011; Pistolesi et al. 2015). In turn, methods for near real-time sampling of tephra fallout have helped to validate dispersion models, and stand as useful tools for prompt hazard assessment. For example, direct sampling by aircraft can determine ash concentration for air traffic safety (Weber et al. 2012), while dense networks of low-cost homemade “ashmeters” can improve ash field-data collection, especially for “small” explosive eruptions and thin distal fallout from larger events (Bernard 2013). There has also been renewed interest in cryptotephras preserved in lake- and ice-cores, study of which has contributed to recognizing and analyzing distal deposits (Cashman and Rust 2019; Hartman et al. 2019). Based on the study of such deposits, multidisciplinary approaches—combining satellite remote sensing data, dispersion modelling and characterization of the optical/physical properties of cryptotephras—have been tested to understand discrepancies in volcanic ash dispersion models (Stevenson et al. 2015; Saxby et al. 2020b).

Finally, rain and wind can easily erode deposits of ash (Fig. 1) and disperse vast quantities of ash into initially unaffected areas. Rainfall and snowmelt events can cause surface runoff of volcanic deposits and the occurrence of debris flows, precluding ash incorporation into a new soil profile (Hayes et al. 2002; Tarasenko et al. 2019). Rainfall can also cause the opposite effect and impede the erosion due to the wetting and cementation of the deposit (Ayris and Rust 2012). Moreover, and under certain weather conditions, aeolian ash remobilization can repeatedly take place for years, decades and even centuries (Hadley et al. 2004; Dominguez et al. 2020). Our understanding of ash resuspension processes has evolved as a result of experimental studies using wind tunnels and high-speed camera imaging (e.g. Etyemezian et al. 2019; Del Bello et al. 2018, 2021).

**Volcanic ash impacts**

Understanding the multifaceted nature of the processes involved in volcanic ash formation helps to better understand its potential impacts on human populations and ecosystems (Fig. 2), thereby allowing possible mitigation actions to be implemented. Post-eruption field observations carried out over the last 20 years have built knowledge on the
consequences of volcanic ash dispersion and fallout. This, integrated with experimental work and quantitative modelling, has permitted the causes and ramifications of ash-related impacts to be explored (Barsotti et al. 2010; Jenkins et al. 2015).

The effects of human exposure to fine ash can range from short-term breathing problems and eye/skin irritation, to potential long-term health issues (Horwell and Baxter 2006). Health concerns extend beyond the duration of an eruption since human activity (e.g. ash clean-up, road traffic) aids remobilization of ash deposits and leads to an additional and prolonged exposure (Andronico and Del Carlo 2016). Since 2003 and the creation of the International Volcanic Health Hazard Network (IVHHN1), several methods for determination of health-relevant characteristics of ash samples and health impact assessment of ash inhalation have been developed (e.g. Le Blond et al. 2009; Damby et al. 2017; Mueller et al. 2020). Extensive ash characterization work and in vitro bioanalytical studies represent an important step forward in understanding the potential effects of ash on human health (e.g. Tesone et al. 2018; Tomášek et al. 2019, 2021).

Research has also contributed to understand volcanic ash impacts on buildings and critical infrastructure (Wardman et al. 2014; Blake et al. 2017). The consequences can range from roof collapse, blockage of roads, modern technology damage to the entire shutdown of community facilities and disruption of supply chains (Wilson et al. 2012; Fig. 2). Regarding aviation infrastructure, between 2000 and 2010, efforts were strongly focused on strengthening volcanic ash warning system, ensuring an accurate forecast of the volcanic activity (Guffanti et al. 2005; Webley et al. 2009). Back then, a global strategy of ash avoidance was followed as the procedure to guarantee flight safety (Casadevall 1994), until the 2010 Eyjafjallajökull eruption. This procedure severely affected civil aviation, triggering unexpected economic repercussions (Mazzocchi et al. 2010), and causing a reassessment of warning systems and communication protocols (Stewart et al. 2016; Reichardt et al. 2018). Consequently, the assessment and reduction of volcanic ash impacts on aviation have become one of the main research areas in the last decade (Song et al. 2014; Lechner et al. 2017).

Blong (1984) also stressed how ash fallout can impact fauna, flora, cultivated land and soils, leading to crop failure and livestock starvation. This point has been followed-up upon by studies such as those of Cronin et al. (2003) and Ayris and Delmelle (2012). Aeolian remobilization of ash can extend the spatial and temporal scale of such impacts (Wilson et al. 2011; Forte et al. 2018), possibly inducing large-scale ecosystem destruction via burial of land to stimulate desertification (Arnalds et al., 2001), and interaction of rainfall, as well as snow melt events can cause erosion, surface runoff of volcanic deposits and even lahar initiation (e.g. Torres et al. 2004; Pierson and Major 2014; Kataoka et al. 2018).

While short-term impacts of ash fall have been shown to be negative, some long(er)-term effects may be beneficial (Ayris and Delmelle 2012; Fig. 2). Weather conditions and time have been shown to lead to the degradation of volcanic ash to form fertile soils so as to increase agricultural productivity (Ugolini and Dahlgren 2002). In turn, the degradation of volcanic ash can influence atmospheric conditions by sequestering CO₂ out of the atmosphere (Fiandis et al. 2016). When deposited in water bodies, fresh volcanic ash can induce physical, chemical and biological effects by releasing soluble elements and increasing turbidity, with negative consequences to the ecosystem and altering the quality of the water supplies (Stewart et al. 2006; Di Prinzio et al. 2021). However, addition of ash can also aid in the “fertilization”
of the ocean surface, which can boost marine primary productivity by injecting bio-available iron (e.g. Langmann et al. 2010; Witt et al. 2017; Vergara-Jara et al. 2021). Further studies have shown that the chemical alteration that ash particles undergo within eruption plumes and during atmospheric transport may as well determine beneficial or detrimental impacts on the deposition systems (e.g. de Moor et al. 2005; Maters et al. 2016; Delmelle et al. 2018).

We end by noting that volcanic ash also has several industrial applications (see Dehn and McNutt 2015). Works from Kupwade-Patil et al. (2016) and Ilham et al. (2020) have shown how volcanic ash as a “fresh” (absorptive properties, chemical reactivity) or weathered (bentonite, pozzolanic component for cement and concrete) material can be used for construction and manufacturing. Such use of ash can constitute a solution for areas regularly affected by ashfall.

**Future challenges**

The past 20 years have been crucial for enlightening and integrating several aspects of the volcanic ash lifecycle. From the mechanisms involved in its generation to the subsequent dispersion, deposition and remobilization processes, all these research topics have benefited from the sophistication of already existing tools as well as from new technologies and more accurate analytical techniques. Yet, due to the inaccessibility of the processes related to the generation of volcanic ash, and despite the hard work done in these last two decades, many questions remain unanswered, and new ones continue to emerge. For instance, although much progress has been made in the understanding of eruptive style transitions (Cassidy et al. 2018), the processes controlling simultaneous explosive-effusive activity need to be better constrained. Experimental studies will continue trying to reproduce, as closely as possible, conditions at different depths, to inform on the dynamics and processes of volcanic ash generation.

Statistically robust analysis of ash deposits remains a challenge. Ash characteristics vary with eruptive styles and distance from the vent for any single event. For such conditions, models to determine an optimal sampling strategy are essential to represent the whole deposit (Spanu et al. 2016; Pioli et al. 2019). Small-size explosive events pose a challenge by their own, as poor stratigraphic records can lead to degrees of high uncertainty on estimating of eruptive volumes (Engwell et al. 2013). Collecting, analyzing and integrating large amounts of fresh samples, representative of the whole deposit, will become a crucial input for more complex, near-real-time and efficient numerical models for ash dispersion and deposition (Freret-Lorgeril et al 2022).

Advances in the statistical modelling and analysis of ash deposits will lead to a more accurate definition of possible impact scenarios for future volcanic events (Connor et al. 2001), and improvements to hazard communication and mitigation tools, such as provisioning better-constrained ash hazard maps. Tools such as machine learning, data assimilation and inverse modelling are promising directions to follow in improving the forecast accuracy for volcanic ash transport or constraint of vent conditions, using satellite data (Prata 2009), aircraft observation (Weber et al 2012) or muography (Nomura et al 2020).

It is known that volcanic ash fallout can strongly affect Earth system and its components or sub-systems: atmosphere, hydrosphere, biosphere and technosphere, the latter representing man-made component. The elements (and sub-elements) within these components or sub-systems (black and blue hexagons respectively, Fig. 3) are intensely interconnected, with a vast degree of interdependency, and create a system or global network. This has, of course, resulted in great progress for our society but at the same time has reinforced its vulnerability (Mani et al. 2021). Elements and sub-elements represent the nodes in the system, and the failure of one of them can trigger cascading effects, severely affecting and pushing other elements of the system towards and beyond tipping points. In the terminology of Chorley and Kennedy (1971), this is a “process-response system”. A volcanic eruption can create such disruption to a process-response system, and Fig. 3 illustrates possible cascading effects (Gasparini and Garcia-Aristizabal 2014) due to volcanic ash impacts on Earth systems. Raising awareness among all parts of the system involved in, and affected by, an eruptive event is one of the biggest challenges of the next decade. As part of this process-response system, implementing mitigation measures is essential, and these need to respect the culture and necessities of the communities at risk (Lowe et al. 2002; Pardo et al. 2015). One way to constructively involve and empower local communities is by training citizen scientists in reporting observations and collecting samples in near-real-time (Wallace et al 2015), as well as building resilience through education (Mei et al. 2020).

Volcanic ash studies increasingly need combined and complementary perspectives from computational, physical, natural and social sciences to avoid getting stuck in conventional views and conceptual models. We hope that the coming decade will further improve our understanding of the life cycle of volcanic ash.
Volcanic Ash
Effect on Earth sub-systems

Legend

- **1st Order Nodes**: Elements within Earth sub-systems
- **2nd Order Nodes**: Sub-elements
- **3rd Order Nodes**: Cascading impacts
- **3rd Order Nodes (repeated)**: Cascading impacts repeated for better layout
- **Cascading positive impacts**
- **Interdependency of cascading impacts**

*Category based on Mani et al. 2021*
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**References**

Aizawa K, Cimarelli C, Alatorre-Ibargüengoitia MA, Yokoo A, Dingwell DB, Iguchi M (2016) Physical properties of volcanic lightning: constraints from magnetotelluric and video observations at Sakurajima volcano, Japan. Earth Planet Sci Lett 444:45–55. https://doi.org/10.1016/j.epsl.2016.03.024

Alfano F, Bonadonna C, Volentik AC, Connor CB, Watt SF, Pyle DM, Connor LJ (2011) Tephra stratigraphy and eruptive volume of the May, 2008, Chaitén eruption, Chile. Bull Volcanol 73(5):613–630. https://doi.org/10.1007/s00445-010-0428-x

Andronico D, Del Carlo P (2016) PM 10 measurements in urban settlements after lava fountain episodes at Mt. Etna, Italy: pilot test to assess volcanic ash hazard to human health. Nat Hazards Earth Syst Sci 16:29–40. https://doi.org/10.5194/nhess-16-29-2016

Arnolds O, Gisladottir FO, Sigurjonsson H (2001) Sandy deserts of Iceland: an overview. J Arid Environ 47:359–371

Ayris PM, Delmelle P (2012) The immediate environmental effects of tephra emission. Bull Volcanol 74(9):1905–1936

Barsotti S, Andronico D, Neri A, Del Carlo P, Baxter PJ, Aspinall WP, Hincks T (2010) Quantitative assessment of volcanic ash hazards for health and infrastructure at Mt. Etna (Italy) by numerical simulation. J Volcanol Geotherm Res 192(1–2):85–96

Behnke SA, Edens HE, Thomas RJ, Smith CM, McNutt SR, Van Eaton AR et al (2018) Investigating the origin of continual radio frequency impulses during explosive volcanic eruptions. J Geophys Res Atmos 123:4157–4174. https://doi.org/10.1002/2017JD027990

Bernard B (2013) Homemade ashmeter: a low-cost, high-efficiency solution to improve tephra field-data collection for contemporary explosive eruptions. J Appl Volcanol 2(1):1–9. https://doi.org/10.1186/2191-5040-2-1

Blake DM, Deligne NL, Wilson TM, Wilson G (2017) Improving volcanic ash fragility functions through laboratory studies: example of surface transportation networks. J Appl Volcanol 6(16). https://doi.org/10.1186/s13617-016-0066-5

Blong RJ (1984) Volcanic hazards: a sourcebook on the effects of eruptions. Academic Press, Sydney

Bonadonna C, Genco R, Gouhier M, Pistolesi M, Cioni R, Alfano F, Hoskuldsen A, Ripepe M (2011) Tephra sedimentation during the 2010 Eyjafjallajökull eruption (Iceland) from deposit, radar, and satellite observations. J Geophys Res 116:B12202. https://doi.org/10.1029/2011JB008462

Bonadonna C, Folch A, Loughlin S, Puempel H (2012) Future developments in modelling and monitoring of volcanic ash clouds: outcomes from the first IAVCEI-WMO workshop on Ash Dispersal Forecast and Civil Aviation. Bull Volcanol 74(1):1–10. https://doi.org/10.1007/s00445-011-0508-6

Carey S, Sparks RSJ (1986) Quantitative models of the fallout and dispersal of tephra from volcanic eruption columns. Bull Volcanol 48:109–125. https://doi.org/10.1007/BF01046546

Casadevall TJ (Ed.) (1994) Volcanic ash and aviation safety: proceedings of the first international symposium on volcanic ash and aviation safety. Bull US Geol Surv Bulletin 2047:450. https://pubs.geolsoc.org/publication/b2047

Cashman KV, Rust AC (2019) Far-travelled ash in past and future eruptions: combining tephrochronology with volcanic studies. J Quat Sci 35(1–2):11–22. https://doi.org/10.1002/jqs.3159

Cassidy M, Cole PD, Hicks KE, Varley NR, Peters N, Lerner AH (2015) Rapid and slow: varying magma ascent rates as a mechanism for Vulcanian explosions. Earth Planet Sci Lett 420:73–84. https://doi.org/10.1016/j.epsl.2015.03.025

Cassidy M, Manga M, Cashman K, Bachmann O (2018) Controls on explosive-effusive volcanic eruption styles. Nat Commun 9:2839. https://doi.org/10.1038/s41467-018-05293-3

Castro JM, Bindeman IN, Tuffen H, Schipper CI (2014) Explosive origin of silicic lava: textural and SD–H2O evidence for pyroclastic degassing during phreatomagmatic effusion. Earth Planet Sci Lett 405:52–61
of accretionary lapilli and the role of liquid bonding. Earth Planet Sci Lett 433:232–240. https://doi.org/10.1016/j.epsl.2015.11.007

Mueller SB, Kueppers U, Ametsbichler J, Cimarelli C, Merrison J, Poret M, Wadsworth FB, Dingwell DB (2017) Stability of volcanic ash aggregates and break-up processes. Sci Rep 7:7440. https://doi.org/10.1038/s41598-017-07927-w

Mueller W, Cowie H, Horwell CJ, Hurley F, Baxter P (2020) Health impact assessment of volcanic ash inhalation: a comparison with outdoor air pollution methods. GeoHealth 4:e2020GH000256. https://doi.org/10.1029/2020GH000256

Nomura Y, Nemoto M, Hayashi N, Hanaoka S, Murata M, Yoshikawa T, Masutani Y, Maeda E, Abe O, Tanaka HKM (2020) Pilot study of eruption forecasting with muromography using convolutional neural network. Sci Rep 10:5272. https://doi.org/10.1038/s41598-020-62342-y

Pardini F, Burton M, de’ Michieli Vitturi M, Corradini S, Salerno G, Merucci L, Di Grazia G (2017) Retrieval and intercomparison of volcanic SO2 injection height and eruption time from satellite maps and ground-based observations. J Volcanol Geotherm Res 331(79):91. https://doi.org/10.1016/j.jvolg.2016.12.008

Papale P (1999) Strain-induced magma fragmentation in explosive eruptions. Nature 397:425–428. https://doi.org/10.1038/17109

Pardo N, Wilson H, Procter JN, Lattughi E, Black T (2015) Bridging Māori indigenous knowledge and western geosciences to reduce social vulnerability in active volcanic regions. J Appl Volcanol 4:5. https://doi.org/10.1186/s13617-014-0019-1

Paredes-Mariño J, Dobson KJ, Ortenzi G, Kueppers U, Morgavi D, Petrelli M, Hess K-U, Laeger K, Porreca M, Pimentel A, Perugini D (2017) Enhancement of eruption explosivity by heterogeneous bubble nucleation triggered by magma mingling. Sci Rep 7:16897. https://doi.org/10.1038/s41598-017-17098-3

Paredes-Mariño J, Scheu B, Montanaro C, Arciniega-Ceballos A, Dingwell DB, Perugini D (2019) Volcanic ash generation: effects of componentry, particle size and conduit geometry on size-reduction processes. Earth Planet Sci Lett 514:13–27. https://doi.org/10.1016/j.epsl.2019.02.028

Pavolonis MJ, Siegel J, Cintiino J (2018) Automated detection of explosive volcanic eruptions using satellite-derived cloud vertical growth rates. Earth Space Sci 5(12):903–928. https://doi.org/10.1002/2018EA000410

Piersson TF, Major JJ (2014) Hydrogeomorphic effects of explosive volcanic eruptions on drainage basins. Annu Rev Earth Planet Sci 42:469–507

Pioli L, Harris AJL (2019) Real-time geophysical monitoring of particle size distribution during volcanic explosions at Stromboli Volcano (Italy). Front Earth Sci 7:52. https://doi.org/10.3389/feart.2019.00052

Pioli L, Bonadonna C, Pistolesi M (2019) Reliability of total grain-size distribution of tephra deposits. Sci Rep 9:10006. https://doi.org/10.1038/s41598-019-46125-8

Pistolesi M, Cioni R, Bonadonna C, Elissondo M, Baumann V, Bertagnini A, Chiari L, Gonzales R, Rosi M, Fracalanci L (2015) Complex dynamics of small-moderate volcanic events: the example of the 2011 rhyolitic Cordón Caurle eruption, Chile. Bull Volcanol 77(1):1–24. https://doi.org/10.1007/s00445-014-0898-3

Pore M, Costa A, Folch A, Marti A (2017) Modelling tephra dispersal and ash aggregation: the 26th April 1979 eruption, La Soufrière St. Vincent. J Volcanol Geotherm Res 347:207–220. https://doi.org/10.1016/j.jvolg.2017.09.012

Pore M, Costa A, Andronico D, S��lo S, Ghouier M, Cristaldi A (2018) Modeling eruption source parameters by integrating field, ground-based, and satellite-based measurements: the case of the 23 February 2013 Etna paroxysm. J Geophys Res Solid Earth 123:5427–5450. https://doi.org/10.1029/2017JB015163

Prata AJ (2009) Satellite detection of hazardous volcanic clouds and the risk to global air traffic. Nat Hazards 51(2):303–324. https://doi.org/10.1007/s11069-008-9273-z

Reichardt U, Ulfarsson GF, Pétursdóttir G (2018) Volcanic ash and aviation: recommendations to improve preparedness for extreme events. Transp Res A Policy Pract 113:101–113. https://doi.org/10.1016/j.tra.2018.03.024

Rose WI, Durant AJ (2009) Fine ash content of explosive eruptions. J Volcanol Geotherm Res 186:32–39. https://doi.org/10.1016/j.jvolg.2009.01.010

Saxby J, Beckett F, Cashman K, Rodger H (2020a) Estimating the 3D shape of volcanic ash to better understand sedimentation processes and improve atmospheric dispersion modelling. Earth Planet Sci Lett 534(15):116075. https://doi.org/10.1016/j.epsl.2020.116075

Saxby J, Cashman K, Rust A, Beckett F (2020b) The importance of grain size and shape in controlling the dispersion of the Vedde cryptopha. J Quat Sci 35(1–2):175–185. https://doi.org/10.1010/jqs.3152

Schipper CI, Castro JM, Tufton H, James MR, How P (2013) Shallow vent architecture during hybrid explosive–effusive activity at Cordón Cauíle (Chile, 2011–12): evidence from direct observations and pyroclast textures. J Volcanol Geotherm Res 262:25–37. https://doi.org/10.1016/j.jvolg.2013.06.005

Shea T, Houghton BF, Gurioli L, Cashman KV, Hammer JE, Hobden BJ (2009) Textural studies of vesicles in volcanic rocks: an integrated methodology. J Volcanol Geotherm Res 190(3–4):271–289. https://doi.org/10.1016/j.jvolg.2009.12.003-%3e

Song W, Hess K-U, Damby DE, Wadsworth FB, Lavaláée Y, Cimarelli C, Dingwell DB (2014) Fusion char-acteristics of volcanic ash relevant to aviation hazards. Geophys Res Lett 41:2326–2333. https://doi.org/10.1002/2013GL059182

Spanu A, de’ Michieli Vitturi M, Barsotti S (2016) Reconstructing eruptive source parameters from tephra deposit: a numerical study of medium-sized explosive eruptions at Etna. Bull Volcanol 78:59. https://doi.org/10.1007/s00445-016-1051-21

Sparks RSJ (1978) The dynamics of bubble formation and growth in magmas: a review and analysis. J Volcanol Geotherm Res 3(1–2):1–37. https://doi.org/10.1016/0377-0273(78)90002-1

Sparks RSJ, Moore JG, Rice CJ (1986) The initial giant umbrella cloud of the May 18th, 1980, explosive eruption of Mount St Helens. J Volcanol Geotherm Res 28(3–4):257–274. https://doi.org/10.1016/0377-0273(86)90002-6

Stevenson JA, Millington SC, Beckett FM, Swindles GT, Thorardson T (2015) Big grains go far: understanding the discrepancy between tephrochronology and satellite infrared measurements of volcanic ash. Atmos Meas Tech 8:2069–2091. https://doi.org/10.5194/amt-8-2069-2015

Stewart C, Johnston DM, Leonard GS, Horwell CJ, Thorardson T, Cronin S (2006) Contamination of water supplies by volcanic ashfall: A literature review and simple impact modelling. J Volcanol Geotherm Res 158(3–4):296–306. https://doi.org/10.1016/j.jvolgeores.2006.07.002

Stewart C, Wilson TM, Sword-Daniels V, Wallace KL, Magill CR, Horwell CJ, Leonard GS, Baxter PJ (2016) Communication demands of volcanic ashfall events. In: Fearnley C.J., Bird D.K., Haynes K., McGuire W.J., Jolly G. (eds) Observing the Volcano World. Advances in Volcanology (An Official Book Series of the International Association of Volcanology and Chemistry of the Earth’s Interior – IAVCEI, Barcelona, Spain). Springer, Cham. https://doi.org/10.1007/978-3-319-11157-0_19

Taddeucci J, Scarlato P, Montanaro C, Cimarelli C, Del Bello E, Freda C, Andronico D, Gudmundsson MT (2011) Dingwell DB (2011) Aggregation-dominated ash settling from the Eyjafjallajökull
volcanic cloud illuminated by field and laboratory high-speed imaging. Geology 39(9):891–894. https://doi.org/10.1130/G32016.1

Tarasenko I, Bielders CL, Guevara A, Delmelle P (2019) Surface crusting of volcanic ash deposits under simulated rainfall. Bull Volcanol 81:30. https://doi.org/10.1007/s00445-019-1289-6

Tesone AI, Vitart RML, Tau J, Maglione GA, Llesiuy S, Tatsar DF, Berra A (2018) Volcanic ash from Puyehue-Cordón Caulle Volcanic Complex and Calbuco promote a differential response of pro-inflammatory and oxidative stress mediators on human conjunctival epithelial cells. Environ Res 167:87–97. https://doi.org/10.1016/j.envres.2018.07.013

Tomašek I, Damby DE, Horwell CJ, Ayris PM, Delmelle P, Ottley CJ, Van Eaton AR, Muirhead JD, Wilson CJN, Cimarelli C (2012) Growth of volcanic ash aggregates in the presence of liquid water and ice: an experimental approach. Bull Volcanol 74:1963–1984. https://doi.org/10.1007/s00445-012-0634-3

Van Wyk De Vries B, Jerram D, Rapprich V, Harris A, Martin D (2018) Geomojos – a symbolic alphabet to communicate Earth Sciences, EGU General Assembly 2018, Vienna, Austria, EGU2018–2951

Vergara-Jara M, Hopwood MJ, Browning TJ, Rapp I, Torres R, Reid B, Achterberg EP (2021) Iriarte JL (2021) A mosaic of phytoplankton responses across Patagonia, the southeast Pacific and the southwest Atlantic to ash deposition and trace metal release from the Calbuco volcanic eruption in 2015. Ocean Sci 17:561–578. https://doi.org/10.5194/os-17-561-2021

Wallace K, Sundgar S, Cameron C (2015) Is Ash Falling?; an online ashfall reporting tool in support of improved ashfall warnings and investigations of ashfall processes, J Appl Volcanol 4:5. https://doi.org/10.1186/s13617-014-0022-6

Wardman JB, Wilson TM, Hardie S, Bogder P (2014) Influence of volcanic ash contamination on the flashover voltage of HVAC outdoor suspension insulators. IEEE Trans Dielectr Electr Insul 21(3):1189–1197. https://doi.org/10.1109/TDEI.2014.6832265

Weber K, Eliasson J, Vogel A, Fischer C, Pohl T, van Haren G, Meier M, Grobëty B, Dahmann D (2012) Airborne in-situ investigations of the Eyjafjallajökull volcanic ash plume on Iceland and over north-western Germany with light aircrafts and optical particle counters. Atmos Environ 48:9–21. https://doi.org/10.1016/j.atmosenv.2011.10.030

Webley PW, Dehn J, Lovick J, Dean KG, Bailey JE, Valic L (2009) Near real-time volcanic ash cloud detection: experiences from the Alaska Volcano Observatory. J Volcanol Geotherm Res 186(1–2):79–90. https://doi.org/10.1016/j.jvolgeores.2009.02.010

Wilson TM, Cole JW, Stewart C, Cronin SJ, Johnston DM (2011) Ash storms: impacts of wind-remobilised volcanic ash on rural communities and agriculture following the 1991 Hudson eruption, southern Patagonia, Chile. Bull Volcanol 73:223–239. https://doi.org/10.1007/s00445-010-0396-1

Wilson TM, Stewart C, Sword-Daniels V, Leonard GS, Johnston DM, Cole JW, Wardman J, Wilson G, Barnard ST (2012) Volcanic ash impacts on critical infrastructure. Phys Chem Earth Part A/B/C 45–46:5e23. https://doi.org/10.1016/j.pce.2011.06.006

Witt V, Ayris PM, Damby DE, CIMarelli C, Kueppers U, Dingwell DB, Wörheide G (2017) Volcanic ash supports a diverse bacterial communities and agriculture following the 1991 Hudson eruption, southern Patagonia, Chile. Bull Volcanol 73:223–239. https://doi.org/10.1007/s00445-010-0396-1

Wright HM, Cashman KV, Mothes PA, Hall ML, Ruiz AG, Le Penec JL (2012) Estimating rates of decompression from textures and investigations of ashfall processes. J Appl Volcanol 4:5. https://doi.org/10.1186/s13617-014-0022-6

Wright HM, Cashman KV, Mothes PA, Hall ML, Ruiz AG, Le Penec JL (2012) Estimating rates of decompression from textures and investigations of ashfall processes. J Appl Volcanol 4:5. https://doi.org/10.1186/s13617-014-0022-6

Wright HM, Cashman KV, Mothes PA, Hall ML, Ruiz AG, Le Penec JL (2012) Estimating rates of decompression from textures and investigations of ashfall processes. J Appl Volcanol 4:5. https://doi.org/10.1186/s13617-014-0022-6

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