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PERSPECTIVES

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.

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Looking Backwards and Forwards in Volcanology: A Collection of Perspectives on the Trajectory of a Science

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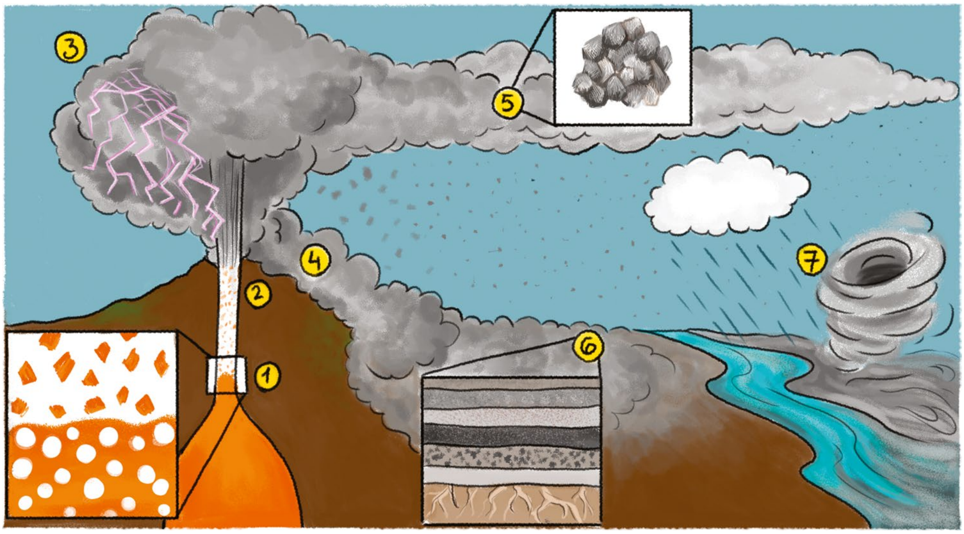

Fig. 1 Volcanic ash lifecycle. From 1 to 7, some of the most relevant processes within the cycle are highlighted: (1) magma fragmentation, (2) secondary ash generation within volcanic conduit, (3) volcanic lightning in the eruptive column, (4) volcanic ash transport by pyroclastic density current, (5) ash aggregation in the volcanic plume (umbrella section), (6) ash deposition blanketing the landscape and (7) ash remobilization by wind and water. The style of Figs. 1 and 2 presented in this article has been set intentionally, so they can be used for outreach and education purposes. This type of conceptualization has been previously used in different publications (Jenkins et al. 2015; Van Wyk de Vries et al. 2018)

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. Eychenne 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; Guéhenneux 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 cryptotephra 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 crytotephras—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 Delmelle 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

Fig. 2 Volcanic ash impacts. Schematic representation of expected short- and long-term impacts due to a moderate-to-large explosive eruption. By no means this cartoon claims to represent all the identified impacts associated with volcanic ash. For a more complete list of the impacts, please refer to the main text on the manuscript

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 (IVHHN[1]), 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; Tomašek 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 CO_2 out of the atmosphere (Fiantis 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"

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[1] www.ivhhn.org

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

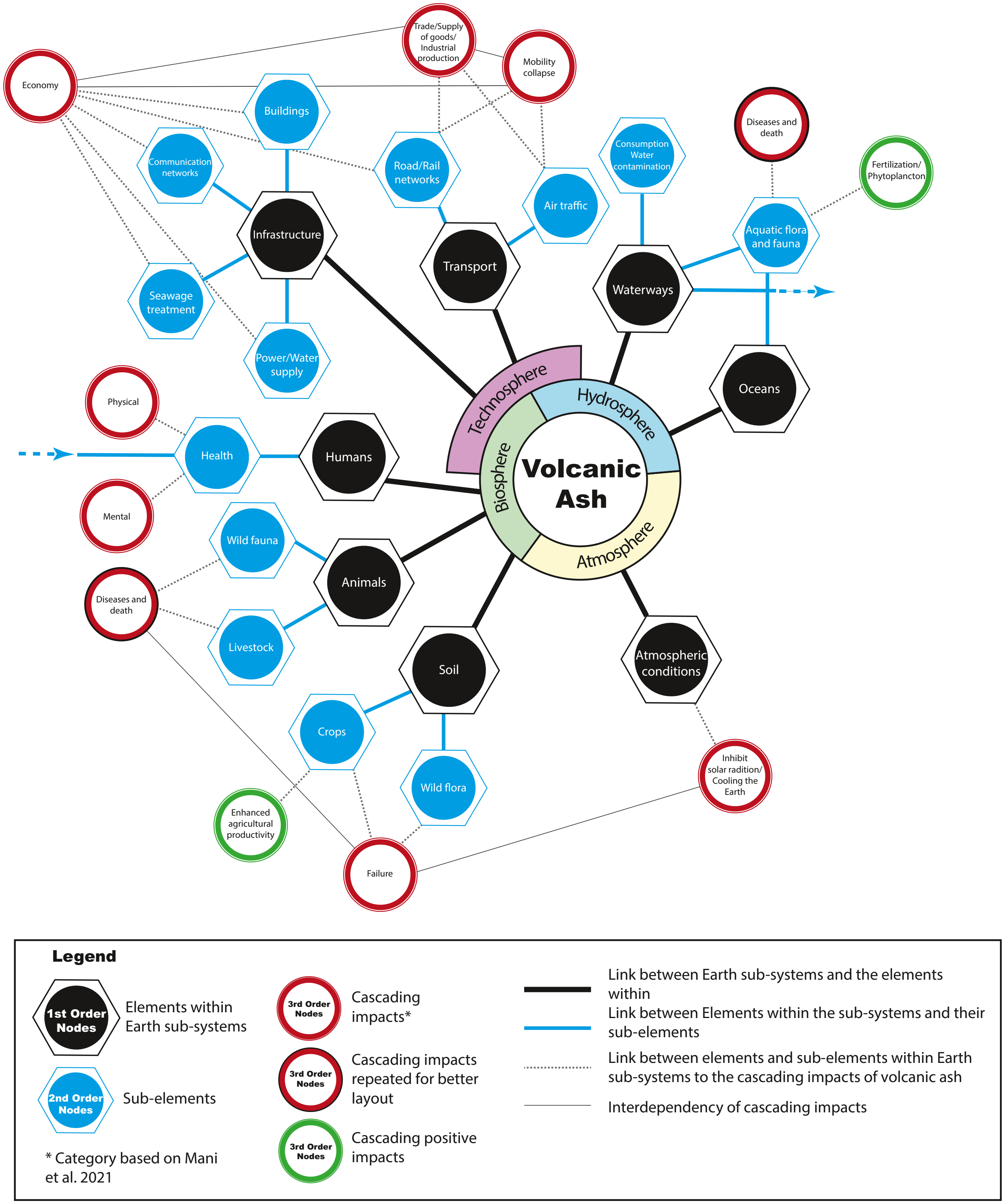
The past 20 years have been crucial for enlightening and integrating several aspects of the volcanic ash lifecycle. From the mechanisms involved in its generation to the subsequent dispersion, deposition and remobilization processes, all these research topics have benefited from the sophistication of 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.


Economy
Trade/Supply of goods/ Industrial production
Mobility collapse
Buildings
Communication networks
Road/Rail networks
Consumption Water contamination
Diseases and death
Fertilization/ Phytoplancton
Air traffic
Infrastructure
Transport
Waterways
Aquatic flora and fauna
Seawage treatment
Power/Water supply
Oceans
Technosphere
Hydrosphere
Biosphere
Atmosphere
Volcanic Ash
Physical
Health
Humans
Mental
Wild fauna
Animals
Diseases and death
Livestock
Soil
Atmospheric conditions
Crops
Wild flora
Inhibit solar radition/ Cooling the Earth
Enhanced agricultural productivity
Failure
Legend
1st Order Nodes
Elements within Earth sub-systems
2nd Order Nodes
Sub-elements
* Category based on Mani et al. 2021
3rd Order Nodes
Cascading impacts*
3rd Order Nodes
Cascading impacts repeated for better layout
3rd Order Nodes
Cascading positive impacts
Link between Earth sub-systems and the elements within
Link between Elements within the sub-systems and their sub-elements
Link between elements and sub-elements within Earth sub-systems to the cascading impacts of volcanic ash
Interdependency of cascading impacts

◂**Fig. 3** Synoptic outline representing possible cascading effects due to volcanic ash impacts on Earth system and its components (or sub-systems). These sub-systems are represented at the core of the diagram, including the atmosphere, hydrosphere, biosphere and technosphere, the latter representing man-made sub-systems. This schematic figure does not pretend to represent all possible effects related to ash fallout and interconnections between the elements on Earth sub-systems, instead attempts to show the fragility of modern society when facing the collapse of some of these system elements (or nodes) due to volcanic ash fallout. There are two orders of nodes, 1st order (black hexagons): *Elements* within the sub-systems, coexisting in society and making it function as we know it; 2nd order (blue hexagons): is the category resulting from breaking down the *Elements*, the *Sub-elements* that are directly vulnerable to an ash fallout. The red and green circles represent the cascading impacts, resulting from the failure of primary and secondary nodes (elements and sub-elements respectively). Red ones are the negative cascading impacts and green ones are the positive ones. The different line types depict the link between sub-systems, elements, sub-elements and cascading impacts

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