MeMoVolc report on classification and dynamics of volcanic explosive eruptions

- Authors
- Authors and affiliations

- C. Bonadonna
- R. Cioni
- A. Costa
- T. Druitt
- J. Phillips
- L. Pioli
- D. Andronico
- A. Harris
- S. Scollo
- O. Bachmann
- G. Bagheri
- S. Biass
- F. Brogi
- K. Cashman
- L. Dominguez
- show 27 more

Forum Contribution

Abstract

Classifications of volcanic eruptions were first introduced in the early twentieth century mostly based on qualitative observations of eruptive activity, and over time, they have gradually been developed to incorporate more quantitative descriptions of the eruptive products from both deposits and observations of active volcanoes. Progress in physical volcanology, and increased capability in monitoring, measuring and modelling of explosive eruptions, has highlighted shortcomings in the way we classify eruptions and triggered a debate around the need for eruption classification and the advantages and disadvantages of existing classification schemes. Here, we (i) review and assess existing classification schemes, focussing on subaerial eruptions; (ii) summarize the fundamental processes that drive and parameters that characterize explosive volcanism; (iii) identify and prioritize the main research that will improve the understanding, characterization and classification of volcanic eruptions and (iv) provide a roadmap for producing a rational and comprehensive classification scheme. In particular, classification schemes need to be objective-driven and simple enough to permit scientific exchange and promote transfer of knowledge beyond the scientific community. Schemes should be comprehensive and encompass a variety of products, eruptive styles and processes, including for example, lava flows, pyroclastic density currents, gas emissions and cinder cone or caldera formation. Open questions, processes and parameters that need to be addressed and better characterized in order to develop more comprehensive classification schemes and to advance our understanding of volcanic eruptions include conduit processes and dynamics, abrupt transitions in eruption regime, unsteadiness, eruption energy and energy balance.

Keywords

Volcanism Eruption dynamics Eruption classification Eruptive products Eruptive processes Eruptive styles

Editorial responsibility: J.D.L. White

Introduction

Eruptive style is primarily a function of magma composition and temperature, magma volatile content and crystallinity, exsolution and degassing processes, magma feeding and discharge rates, conduit geometry and mechanical strength, magma reservoir pressure and the presence of external water. Key processes and parameters that characterize explosive eruptions are only partially understood, generating confusion in the way we classify and categorize eruptions, especially in the cases of small-moderate-scale eruptions which, owing to their high frequency, have significant economic impact. Conversely, the classification of eruptive activity is generally based on a small, selected set of parameters, directly observed during eruptions or derived from their deposits, that only partially represent the natural complexity of the activity (e.g. Walker 1973; Newhall and Self 1982; Pyle 1989; Bonadonna and Costa 2013). For example, specific classification categories, such as violent Strombolian, Vulcanian or sub-Plinian, have often been attributed to small- or moderate-sized eruptions based only on the eruption size (from plume height or product dispersal), without full consideration of the eruption dynamics. The lack of understanding of the diagnostic signatures of these kinds of eruptions, and the processes involved, also leads to new attempts of describing explosive eruptions that vary from volcano to volcano, e.g. the delineation of lava/fire fountaining activity at Etna with respect to that in Hawai’i, the distinction between major and paroxysmal eruptions at Stromboli or between different types of Vulcanian activity at volcanoes dominated by silicic lava domes with respect to volcanoes characterized by more mafic magmas and ash emissions. This is all symptomatic of our limited current understanding of explosive volcanism, with obvious implications for assessing hazards. It is important to stress that explosive volcanism can also include effusive phases (e.g. lava flows, dome growth) and outgassing, which should also be considered in order to develop a comprehensive understanding of the diversity of eruptive dynamics. Of concern is that limitations in our ability to categorize and classify eruptions may hinder our progress in understanding eruptions and communication of hazards.

Early studies of physical volcanology, and proposals of classification schemes, were mainly based on visual observations of eruptive phenomena at specific volcanoes and eventually evolved to take into account deposit quantification (e.g. Mercalli 1907; Lacroix 1908; McDonald 1972; Williams and McBirney 1979; Walker 1973). In practice, due to its nearly ubiquitous presence in the different eruptive styles, tephra fallout is traditionally the main type of deposit investigated in order to provide insights into the eruptive dynamics (here, tephra is considered in the sense of Thorarinsson (1944), i.e. collective term used to describe all particles ejected from volcanoes irrespective of size, shape and composition). However, by considering only the dispersal of tephra, and not, for example, the deposits’ internal stratigraphy, the complex and unsteady source dynamics typical of small-moderate explosive eruptions cannot yet be fully captured *post facto* from the deposits. Many eruptions show hybrid features, starting with one eruptive style but terminating with another, resulting in a complex stratigraphic record that is difficult to classify. Yet, other eruptions have characteristics that are gradational between the defined eruptive styles, such as Strombolian and Vulcanian, reflecting transitions in physical phenomena that are as yet imperfectly understood and quantified. Some eruptions would be better described based on the analysis of all volcanic products (e.g. volume ratio between erupted lava and tephra fallout or volume ratio between tephra-fallout and pyroclastic-density-current (PDC) deposits), and especially of the products related to those phases of the eruption marking a shift in the eruptive style. Importantly, ignimbrite-forming eruptions, which include some of the largest on Earth, cannot be simply classified by our present schemes. Furthermore, when dealing with deposits from the rock record, there is often large uncertainty in associating a timescale with the internal stratigraphy, so that layering and stratification could be related not only to changes of dynamics during a rather continuous event but also to quite distinct eruptive pulses.

Progress in physical volcanology, combined with increased capability in monitoring and measuring explosive eruptions and in the experimental simulation and numerical modelling of the related physical processes, has highlighted how the description of eruptive behaviour should be based on a combination of deposit features, including deposit thinning, deposit grain size, textural features, componentry, density and porosity of products (and their variation through time), together with geophysical measurements (e.g. volcanic tremor, acoustic measurements) and visual observations (e.g. explosion frequency, plume/jet description) of the eruption itself. The development of a comprehensive understanding of the parameters driving explosive volcanism covering the whole range from weak to powerful explosions, from small to lava-forming events and from simple to complex, hybrid eruptions, represents one of the main challenges faced by the volcanological community. Present classifications are mainly based on the characteristics of tephra-fallout deposits, or on direct observations, while relatively little attention is paid to the entire dynamics and time-related variability of different eruptions.

A comprehensive approach to the description of explosive volcanic eruptions can only result from the combined efforts of many scientists working in various subdisciplines. A multidisciplinary group of the international volcanological community gathered at the University of Geneva on 29–31 January 2014 under the sponsorship of the MeMoVolc Research Networking Programme of the European Science Foundation and the Department of Earth Sciences of the University of Geneva in order to (i) review existing classification schemes and discuss the needs of eruption classification; (ii) fill the gap between recent advances in geophysical, modelling and field strategies and current classification schemes and (iii) investigate how the contributions from different subdisciplines can be combined. Specific objectives were to (i) review new advances in our mechanistic understanding of a broad range of eruptive styles and their relation to eruption classification; (ii) identify the critical parameters that drive and characterize explosive volcanism of different types; (iii) determine the main processes that control the temporal evolution of eruptions, and the frequently observed changes in eruptive style; (iv) identify research priorities that could allow new advances in the characterization, understanding and classification of volcanic eruptions and (v) suggest a roadmap for producing a rational and comprehensive classification scheme. This consensual document attempts to summarize the outcome of two and a half days of talks, posters, breakout sessions and plenary discussions (see also the workshop website for programme details: http://www.unige.ch/hazards/MeMoVolc-Workshop.html).

Main general classification schemes used to characterize volcanic eruptions

We can distinguish between "general" (those not based on specific volcanoes) and "local" classification schemes (those that mainly consider local eruptive features at specific volcanoes). General schemes are needed to make global comparisons, to better understand the general trends of explosive volcanoes and to better identify the key processes that distinguish eruptive styles. Local classifications can capture local trends and specific eruptive patterns and, therefore, are crucial to local hazard assessments. Here, we summarize the main general classification schemes used in the literature and identify some of their shortcomings.

The first general classification schemes of volcanic eruptions identified "type volcanoes", made associations with specific eruptive features, were mostly qualitative and were biased towards the more frequent small to moderate eruptions (e.g. Mercalli 1907; Lacroix 1908; Sapper 1927; Perret 1950). They were eventually replaced by schemes based on processes and quantitative descriptions, with special focus on the characteristics of tephra-fallout deposits (e.g. Walker 1973, 1980; Self and Sparks 1978; Wright et al. 1980) (Table 1). Five parameters were introduced for estimating the scale of explosive eruptions (e.g. Walker 1980): (i) magnitude (volume of erupted material typically converted to dense rock equivalent (DRE)), (ii) intensity (i.e. discharge rate; volume of ejecta per unit time), (iii) dispersive power (related to the total area of dispersal and, therefore, to plume height), (iv) violence (related to kinetic energy) and (v) destructive potential (related to the extent of devastation). Eruptive styles (Table 1) were determined based on two parameters (Walker 1973): F, fragmentation index (indicator of the explosiveness of the eruption), and D, area of pyroclastic dispersal (indicator of the column height). Specifically, D is the area enclosed by an isopach contour representing 1 % of the maximum thickness ($0.01\ T_{\max}$), and F is the percent of tephra <1 mm, measured along an axis of dispersal where the isopach is 10 % of $T_{\max}$ ($0.1\ T_{\max}$). Eventually, the styles representing violent Strombolian, ash emissions, Vesuvian and the silicic equivalent of surtseyan were discarded, and new terms such as phreatoplinian and ultra-Plinian were introduced (Walker 1980; Self and Sparks 1978; Cas and Wright 1988). However, the term violent Strombolian has remained in the literature and has been preferred by Valentine and Gregg (2008) to the new term introduced by Francis et al. (1990) (i.e. microplinian) mostly because of its widespread use, and because it does not suggest the injection above the tropopause as does the term Plinian.

Table 1

Categories used to classify explosive volcanic eruptions as reported in main "general" classification schemes (the most used categories are highlighted in grey). Mcdonald (1972) is adjusted from Mercalli (1907), Lacroix (1908) and Sapper (1927); Williams and McBirney (1979) is a simplification of Mercalli (1907), Sonder (1937), Rittmann (1962), Gèze (1964) and Walker (1973).

Open image in new window

	Macdonald (1972)	Walker (1973, 1980)	Williams and McBirney (1979)	Newhall and Self (1982)	Pyle (1989
Lava lake					
Basaltic flood	✓				
Hawaiian	✓	✓	✓	✓	
Strombolian	✓	✓	✓	✓	✓
Violent Strombolian	✓	✓			
Microplinian					
Strombolian paroxysm	✓				
Vulcanian	✓	✓ Vesuvian	✓	✓	
Peléean	✓ variety of Vulcanian		✓		
subplinian		✓			✓
Plinian	✓ variety of Vulcanian	✓	✓ Krakatoan	✓	✓
Ultraplinian		✓		✓	✓
Rhyolitic flood	✓				
Ash emission		✓ conduit clearing			
Ultravulcanian	✓ no magma				
Gas eruption	✓ no magma				

This new approach to eruption classification was pioneering by linking volcanic eruptions and pyroclastic deposits, and it allowed for significant progress in physical volcanology based on the identification and analysis of common features of eruptions having similar characteristics. However, shortcomings included (i) the difficulty in determining *F* and *D*; (ii) the definition of fragmentation index, which is not only controlled by magma fragmentation but also by premature fallout of fine ash due to aggregation processes; (iii) the inability to coherently represent eruptions fed by low-viscosity magmas (e.g. Andronico et al. 2008; Houghton and Gonnermann 2008); (iv) the difficulty of classifying eruptions with poorly preserved deposits; (v) the inability to account for volcanic products other than tephra fallout (e.g. Pioli et al. 2009); (vi) the difficulty of discriminating the wide range of mid-intensity eruptions (small-moderate eruptions of Bonadonna and Costa (2013)); (vii) the usual association between hydromagmatism and ash-dominated eruptions and (viii) the absence of hybrid and multistyle eruptions.

Williams and McBirney (1979) suggested that a rigid classification of eruptions is impossible, mainly because eruptive style and products might change significantly during a single eruption, but that, nevertheless, classifications provide a common vocabulary for communication and comparing eruptions. They also thought that most of the existing classification schemes at the time were too complex to be used and tried to better define existing terms in order to simplify the schemes (e.g. Table 1). Pyle (1989) and Bonadonna and Costa (2013) introduced new schemes based on the characterization of tephra-fallout deposits, which were easier to apply and mostly concerned small-moderate, sub-Plinian, Plinian and ultra-Plinian eruptions (Table 1). In fact, small-moderate eruptions and eruptions characterized by magma/water interaction were recognized as impossible to distinguish solely on the basis of the parameters considered (i.e. plume height, mass eruption rate (MER), deposit thinning and grain size decrease). These new classification schemes still neglected volcanic products other than tephra fallout, as well as hybrid and multistyle eruptions. General shortcomings of all process-based classification schemes described above include (i) the difficulty of representing all eruptions on one single diagram (in particular effusive together with explosive events, and large explosive eruptions together with small-moderate explosive eruptions); (ii) the incomplete accounting of all volcanic behaviours, duration and products (i.e. schemes are based on tephra-fallout deposits and typically neglect important other products and processes, such as pyroclastic density currents, lava flows, gas) and (iii) the impossibility of fully describing complex eruptions with variable styles.

Newhall and Self (1982) introduced a classification strategy that assigned a certain erupted volume and plume height range to the most common eruptive styles: the volcanic explosivity index (VEI). This logarithmic scale ranges from “non-explosive” Hawaiian eruptions (VEI 0; volume < 10,000 m^3; plume height < 100 m) to “very large” ultra-Plinian eruptions (VEI 5–8; volume > 1 km^3; plume height > 25 km). This scale is widely used in global databases (e.g. GVP, http://www.volcano.si.edu; Siebert et al. 2010) and hazard/risk assessments because it offers a comforting analogue to the more widely used earthquake magnitude scale. The main shortcomings of this approach include (i) the implicit assumption of a link between magnitude and plume height and, therefore, intensity; (ii) a gap between modern eruptions that are typically defined by plume height, versus ancient eruptions that are typically defined by erupted volume; (iii) impossibility of classifying effusive (lava) eruptions, which by default are assigned a VEI of 0 or 1; (iv) ambiguity in the definition of VEI 0 that covers at least six orders of magnitude of eruptive volume (e.g. Houghton et al. 2013); (v) ambiguity in the definition of erupted volume that in the global databases sometimes includes deposits of PDCs (as per the original definition of VEI) and sometimes only tephra-fallout deposits; (vi) the difficulty of characterizing long-lasting eruptions associated with multiple phases of varying style and intensity and (vii) the difficulty of estimating the tephra-fallout volume of the cone edifice built during small-moderate eruptions that usually is not considered in the calculation of the total erupted mass (in fact, in this type of eruptions, the volume of the material forming the cone may be several times larger than the mappable medial to distal tephra-fallout sheets).

Regardless of their shortcomings, some categories have been used by many classification schemes, while others have been abandoned in more recent works (Table 1). It is clear how classification schemes have been simplified with time, trying also to avoid nomenclature based on specific volcanoes (as suggested long ago by Rittmann 1944). Plinian is clearly universally accepted, as it is used in all classification schemes proposed, demonstrating the comparative ease of classifying relatively large eruptions. Hawaiian, Strombolian, Vulcanian, sub-Plinian and ultra-Plinian have also been used by most authors, even though their definitions can be complex and ambiguous. As an example, lava fountains frequently observed in recent years at Etna typically have been characterized by the formation of eruption columns >2 km above the cone and so mostly fit in the violent Strombolian to sub-Plinian field of Walker (1973) rather than in the Hawaiian to normal Strombolian spectrum (e.g. Andronico et al. 2014a, b). Finally, even though ultra-Plinian was used by many authors, we consider this category as a special case because it was based on only one eruption (i.e. the Taupo 1800a eruption, New Zealand; Walker 1980), and recent evidence shows that the large footprint of this apparently single-fallout layer is an artefact of a previously unrecognized shift in the wind field during a fairly complex eruption, rather than indicating extreme eruptive vigour. When the associated deposit is subdivided into subunits, the Taupo eruption is better classified as Plinian (Houghton et al. 2014). Additional field evidence for possible ultra-Plinian deposits include the Campanian Ignimbrite; Rosi et al. 1999) and the 1257 AD Samalas eruptions (Lombok, Indonesia; Vidal et al. 2015). Separate from specific examples, but in accord with the Bonadonna and Costa (2013) classification, the upper limit of ultra-Plinian eruptions can be defined on the basis of MER, based on the conditions for column collapse (i.e. greater than ~10^{9} kg s^{-1}; e.g. Koyaguchi et al. 2010).

Critical processes and parameters that drive and characterize explosive volcanism of different types

A list of processes and parameters that drive and characterize explosive volcanism of different types is compiled in Table 2. All these processes are significant in controlling and defining eruption dynamics, and many of them are considered when studying the products of explosive eruptions. Despite this, a systematic and complete study of these parameters and of their interrelationships is presently lacking.

Table 2

Main processes and parameters characterizing volcanic explosive eruptions

Initial conditions
1. Magma reservoir size, shape and overpressure and evolution with time
2. Magma properties (e.g. composition, temperature, phenocryst content, dissolved volatiles, exsolved gas) and their evolution with time
3. Magma mixing and mingling
Conduit magma dynamics
4. Conduit width, length, shape, pressure and their evolution with time
5. Magma supply rate and relationships with magma reservoir dynamics
6. Magma decompression rate
7. Magma crystal content and crystallization kinetics
8. Magma outgassing (through the conduit walls or at the vent)
9. Porosity and permeability and their evolution with time
10. Dynamic changes in magma rheology (e.g. shearing, degassing, crystallization, viscous heating)

11. Fragmentation level, mechanisms and efficiency
12. Plug formation (shallow viscosity and pressure gradients)
Eruptive processes and parameters
13. Crater/vent geometry and its evolution with time
14. Pressure, velocity, gas content, temperature and density of erupted mixture at vent and their evolution with time
15. Mass eruption rate and its evolution with time
16. Total grain size distribution and its evolution with time
17. Equilibrium or non-equilibrium between particles and gas (controls generation of shocks, thermal structure and timescale)
18. Plume height, temperature, density and collapse conditions
19. Partitioning of mass into plume, pyroclastic density currents and lava flows
External factors
20. Atmospheric conditions (e.g. wind direction and speed, air entrainment, humidity, temperature, density)
21. Magma/water-ice interaction
22. Crustal stress/earthquakes
23. Thermomechanical interaction with country rock (including country rock entrainment and conduit wall collapse)
24. Caldera collapse timing, mechanism and extent

Research priorities

Based on Table 2, we have identified a number of key phenomena whose processes and parameters require more investigation and research. These include the following:

Conduit processes and dynamics

Processes and parameters that require a better understanding and characterization include multiphase magma rheology (non-linearity on different spatial and temporal scales), volatile exsolution and vesiculation processes (kinetics, disequilibrium and the interaction between different volatile phases), fragmentation dynamics and their relationship to pyroclast size distribution and shape, vent and conduit geometric complexity and changes to it during eruption, magma-water interaction, magma interaction with country rock and the effects of crustal and local stresses on conduit dynamics (e.g. Costa et al. 2009, 2011; de' Michieli Vitturi et al. 2013; Woods et al. 2006).

Abrupt transitions in eruption regime

Specific parameters causing abrupt transitions (e.g. major changes in magma composition and rheology, degassing behaviour, groundmass crystallization, dramatic changes in conduit/vent geometry) should be investigated and better defined—for example, through perturbation analysis—with the aim of identifying dimensionless scaling relationships that could characterize controls on instability. Similarly, uncertainty quantification and sensitivity analysis investigations of the effects of conduit processes on the eruptive style should be extended to identify the key controls on eruptive dynamics (e.g. Colucci et al. 2014).

Unsteadiness

Many eruptions are characterized by unsteadiness, involving fluctuations of eruption intensity on a wide range of length scales and timescales (subsecond to hours or days). For example, the scale of unsteadiness (periodicity and amplitude of fluctuations) increases when passing from Plinian (quasi-steady), through sub-Plinian (oscillating, sustained, short-lived column), to violent Strombolian (lava fountain-fed, discontinuous, pulsating column) to Vulcanian (discrete explosions separated by pauses). Unsteadiness should be quantified with continuous measurements of MER, plume height and meteorological conditions at the highest possible resolution or with indirect measurements of tephra-fallout bedding and grain size variations (in particular for post-eruption analysis).

Open questions that cannot be answered until a better understanding is acquired include:

- How do we define unsteadiness (e.g. cyclic versus irregular pulsating activity; steady, quasi-steady or highly unsteady)?
- How do we quantify unsteadiness (e.g. could we quantify unsteadiness using measurements of plume/jet height, geophysical observations and/or gas emissions? How can unsteadiness be measured in a deposit?)?
- How do we distinguish between source-generated unsteadiness related to eruptive fluctuation at the vent and process-generated unsteadiness generated, for example, by changes in wind direction and speed (e.g. Houghton et al. 2014)?

- What are the causes of unsteadiness (e.g. ascent rate too low to sustain gas supply, ascent rate too low to keep pace with discharge, transition from open to closed system degassing, magma-water interaction, syn-eruptive changes in magma rheology or magma permeability able to modulate magma discharge, interaction with country rock, interaction with the atmosphere, unsteady dynamics of the column, unsteady sedimentation processes due to local instabilities)?
- What are the relevant timescales for unsteadiness? Which timescales can be measured and quantified? Can the characteristic timescale of conduit processes be defined and compared with the characteristic time of plume ascent?

Eruption energy and energy balance

The possibility of defining eruptive styles in terms of energy balance (partitioning between thermal, kinetics, fragmentation energy) and energy flux (rather than total energy) has been identified as a potential alternative to classifications based on erupted mass and plume height, but requires further investigation (e.g. Yokoyama 1956, 1957a,b; Hedervari 1963; Garces 2013). It is not yet practical to derive energy partitioning from deposits of past eruptions.

Objectives of eruption classification

The objectives of modern eruption classifications include (i) scientific understanding (i.e. to simplify a complex system by identifying leading-order processes and to aid comparison between different eruptions or volcanoes), (ii) eruption scenario reconstructions for hazard and risk assessment and (iii) facilitation of science and hazard communication (i.e. communication with the scientific community, the public and civil defence institutions). In all cases, eruptions can be described differently depending on whether they are observed in real time or characterized based only on their deposits. Hazard communication should be a simple phenomenological description based on the simplification of scientific understanding. An ideal approach would be to have classification systems based on fairly easily and rapidly measured parameters, so that the system could be applied even in near real time during an ongoing event. Tables 3 and 4 summarize the relevant parameters that can be observed, measured and derived and might be related to the scale of eruptions.

Table 3

Relevant parameters to be described in real-time analysis (observation/monitoring based) and to be possibly associated with uncertainty estimates

Eruption onset and duration	Observed
Plume/jet height	Measured/derived from geophysical monitoring,

	remote sensing and video recording
Mass eruption rate (MER)	Derived from either plume height (depending on observed atmospheric conditions) and/or from geophysical monitoring and remote sensing. MER of lava flows could be directly measured.
Erupted volume/mass	Mostly tephra-fallout mass derived from MER and duration; pyroclastic density currents and lava masses derived from remote sensing
Exit velocity	Derived from geophysical monitoring and video recording
Energy (seismic, infrasonic, thermal, potential/kinetic), energy flux and ratios between the different types of energy	Measured/derived from geophysical monitoring and remote sensing
Unsteadiness (number/frequency of pulses)	Observed/derived from geophysical monitoring and video recording
Relevant atmospheric parameters (e.g. wind, humidity, lightning)	Measured/derived
Sedimentation rate	Measured
Gas flux and composition	Measured

Table 4

Relevant parameters to be described in post-eruption analysis (deposit based) and to be possibly associated with uncertainty estimates

Erupted volume/mass of different volcanic products	Derived (from deposits)
Plume height	Derived (from tephra-fallout deposits)
Mass eruption rate (MER)	Derived (mostly from plume height)
Duration	Derived (from combining MER and mass)
Exit velocity	Derived (from proximal ballistic)
Total grain size distribution	Derived (from deposits)

Thickness and maximum clast size distribution	Derived from measurements at individual sites
Deposit density	Measured per site
Componentry	Measured per site
Shape, texture, crystallinity and density of juvenile clasts	Measured on selected clasts
Unsteadiness	Derived (from bedding/grading)
Wind direction and speed	Derived (from tephra-fallout deposits)
Magma composition	Measured on selected clasts
Magma rheology	Measured or derived from data on composition and crystallinity

Derived parameters are estimated based on dedicated models

A roadmap for a more comprehensive approach to eruption classification

Shortcomings of current systems of classification, in particular associated with the small-moderate eruptions and the diversity of phenomena that can occur within a single event (e.g. PDCs, lava), can be addressed by making these systems adaptable to multiple levels of detail and multiparameter space, particularly including unsteadiness and duration. In fact, it may be useful to describe volcanic eruptions using a qualitative classification with numerical information (i.e. an eruption descriptor plus numerical information) following an “event tree” approach. From the identification and analysis of common features using this kind of categorization, we may find a way to classify rationally a spectrum of eruption styles using a minimal number of descriptors. Critical parameters include deposit geometry, dispersal, plume height, eruption duration, mass associated with each phenomenon, grain size, presence of unsteadiness, types and characteristics of juvenile material and abundance of wall-rock fragments.

In particular, in real time, classification should be based on observations of phenomena (e.g. Table 3), while, for post-eruption descriptions, classification should be based on the quantification of volcanic products (e.g. presence of tephra-fallout/PDC/lava deposits, maximum clast size, thickness distribution, layering/bedding of deposit) and deposit-derived parameters (e.g. plume height, volume, total grain size distribution) (Table 4). In both cases, phases or layers need to be described based on an event tree approach and to include all primary processes known, in the greatest detail possible (e.g. plume/no plume, lava flow/no lava flow, PDCs/no PDCs).

Given the limitations of current eruption classification schemes, we emphasized the importance of continuing the practice of providing clear, objective descriptions of eruption phenomena and products, thereby avoiding the issue of pigeonholing. When available, parameters indicated in Tables 3 and 4 should be provided as a priority. The strategy used to derive these parameters and the classification scheme used (if the eruption was classified) should also be indicated. When possible, real-time and post-eruption deposit-based descriptions should be integrated, because they often provide different and complementary information. Some detailed examples are provided in Appendix A.

Concluding remarks and open questions

This workshop allowed participants to assess the main advantages and shortcomings of existing eruption classification schemes and to identify open questions and research priorities that could help improve our understanding of volcanic explosive eruptions. Based on our thematic breakout sessions and plenary discussions, we reached a number of conclusions:

1. 1.
Existing classification schemes fail to collate all volcanic eruptions in one simple diagrammatic form and do not account for all volcanic behaviours and products. In addition, we identified that eruption categories used by most schemes include Hawaiian, Strombolian, Vulcanian, sub-Plinian, Plinian and ultra-Plinian. There is a need for the community as a whole to work collectively towards improved classification of eruptions and their deposits.
2. 2.
The main parameters and processes characterizing volcanic eruptions include initial conditions, conduit-related magma dynamics and external factors (see Table 2).
3. 3.
Classification schemes need to be objective, focused and designed for specific goals (e.g. scientific understanding, hazard/risk assessment, communication with the public, civil defence institutions and the scientific community) and sufficiently clear and simple to promote accurate transfer of knowledge and scientific exchange.
4. 4.
Classification should be based on clearly defined observables and aimed at identifying the main processes. We found that most existing classification schemes are based on processes (e.g. Walker 1973, 1980; Pyle 1989; Bonadonna and Costa 2013), but the parameters do not capture all relevant volcanic phenomena and are too broad to distinguish between transient versus sustained eruptions or steady versus unsteady behaviours.

5. 5. Classification schemes should be comprehensive and encompass a variety of eruptive styles and volcanic products, including, for example, lava flows, PDCs, gas emissions and cinder cone or caldera formation. While we have focussed on subaerial eruptions, classification should extend to submarine eruptions.
6. 6. Real-time classifications should be based on quantitative observations of phenomena (Table 3), whereas post-eruption classifications should be based on the quantification of volcanic products and deposit-derived parameters (Table 4). Both real-time and post-eruption descriptions should include uncertainty estimates. When possible, real-time and post-eruption descriptions should be integrated because they often provide different and complementary information.
7. 7. Currently, we do not have a system that can be used for all eruptions. It might be possible in the future to have a more comprehensive classification scheme, but it is likely that it will be associated with a different way of measuring eruptions (e.g. energy balance) instead of evolving from existing schemes.
8. 8. None of the existing schemes consider the distinction between steady and unsteady processes. We identified that unsteadiness is, in fact, a key factor for describing volcanic eruptions, but also concluded that we do not yet have effective means of classifying unsteadiness itself. Future eruption classification schemes should incorporate the concept of unsteadiness.
9. 9. Classification schemes should also describe eruption duration to distinguish between short-lived and long-lasting eruptions (e.g. the 2015 eruption of Calbuco volcano, Chile, e.g. Castruccio et al. 2016, versus the 2011 eruption of Cordón Caulle volcano, Chile, e.g. Collini et al. 2013).
10. 10. Open questions, processes and parameters that need to be addressed and better characterized in order to develop more comprehensive classification schemes and to progress in our understanding of volcanic eruptions include conduit processes and dynamics, and of abrupt transitions in eruption regime, unsteadiness, eruption energy and energy balance.

Finally, we note the advice of Williams and McBirney (1979) who recognized that even though some specific nomenclature to classify volcanic eruptions is poorly defined, it has become too firmly entrenched in volcanological literature to abandon. The best improvements are to define old terms more clearly and introduce new ones only when necessary. As a result, we envisage that a future classification scheme will retain some existing terms but will need to better define them based on the parameters we identify for the classification of eruptions in real time and for post-eruption classification (Tables 3 and 4). Based on the frequency of use (Table 1), we expect terms such as Hawaiian, Strombolian, Vulcanian, sub-Plinian, Plinian and ultra-Plinian to be part of future classification, but we suggest that they be combined with a phenomenological and quantitative description (possibly including uncertainty estimates), such as that reported in Appendix A, which provides key parameters including (i) plume/jet height, duration, MER, erupted mass/volume, energy, exit velocity, gas flux and composition, atmospheric conditions and unsteadiness *for real-time classification* and (ii) thickness and maximum clast size distribution, deposit density, deposit componentry, shapes of juvenile clasts, deposit layering, pyroclast composition/crystallinity, erupted mass/volume of different volcanic products, total grain size distribution, plume height, MER, duration, exit velocity and wind direction and speed *for post-eruption classification*. In addition, information to identify magma/water interaction and quantify componentry should be provided together with the key parameters listed above. We also conclude that a few additional eruption categories might need to be added, because some eruptions cannot be described by the five most commonly used categories identified in Table 1, e.g. non-explosive, phreatic, continuous ash emissions/ash venting.

Notes

Acknowledgments

The workshop was made possible by the financial support of the Measuring and Modelling of Volcano Eruption Dynamics (*MeMoVolc*) ESF Network and of the Earth Sciences Department of the University of Geneva. We thank also James White, Ray Cas, Marcus Bursik and an anonymous reviewer for constructive comments that improved the final manuscript.

Appendix A

Examples of descriptions and classifications of volcanic eruptions

Eruption classification needs to be fit for purpose (e.g. scientific understanding, hazard/risk assessment, communication with public, civil defence institutions and scientific community) and clear and simple enough to promote accurate transfer of knowledge and scientific exchange. It might vary depending on whether the classification is based on direct observations (i.e. real time) or on volcanic deposits (i.e. post-eruption). In particular, in real time, classification should be based on quantitative observations of phenomena (Table 3), while, for post-eruption descriptions, classification should be based on the quantification of volcanic products and deposit-derived parameters (Table 4). Here, we present some concrete examples developed by workshop participants. For two eruptions (i.e. Montserrat, 17

September 1996; Etna, 12 January 2011), we provide both types of descriptions (real time and post-eruption).

Examples of real-time descriptions

Gas piston event at Pu’u ‘O’o, Hawaii (23 February 2002)

Basaltic lava flow from vent at foot of Pu’u ‘O’o south wall begins at 19:59 and extends 100 m east by 20:15 (5 m wide proximally). A bulk volume flow rate of 0.26 $m^3 s^{-1}$ for the lava flow was derived based on an emplacement duration of 16 min, which can be converted into a MER value of 414 ± 219 kg s^{-1} by using the vesicle-corrected density of Harris et al. (1998) (i.e. 1590 ± 840 kg m^{-3}). Continuous spattering at vent was observed throughout emplacement. Spattering transits to bubble bursts at 20:41. Bursts increase in frequency to more than 1 per second by 20:45. At 20:45, bubble bursting and lava emission terminated by onset of gas jet with loud roar to 25(?) m. Waning gas jet until 20:15. Vertical blue gas jet with few diffuse, small (cm-sized) incandescent particles. Spatter-bubble-jet cycle recommences; next jet at 21:16. It was classified as gas piston event type “c” according to Marchetti and Harris (2008). Gas flux was not measured.

Montserrat, West Indies (17 September 1996)

A major phase of lava dome collapse began at 11:30 am on the 17 September 1996, continued for 9 h and waned after 8:30 pm. The explosive eruption began at 11:42 pm and had finished by 00:30 am on 18 September. Seismic energy on the RSAM record peaked at about midnight and then declined exponentially. A vertical plume was intercepted by a commercial jet at 11.3 km, which is associated with a dense rock equivalent (DRE) discharge rate of magma of 1300 $m^3 s^{-1}$(based on Sparks et al. 1997). Assuming a constant discharge rate over the whole 48-min duration, a DRE volume of about 3.7×10^6 m^3 was obtained. From weather satellite images (Satellite Analysis Branch of NOAA/NESDIS), plume transport was both to the west and to the east by regional trade and antitrade winds with a maximum speed at tropopause of 17 m s^{-1}. Pumice and lithic lapilli fell widely across southern Montserrat. Classified as small-moderate based on plume height and MER according to Bonadonna and Costa (2013).

Etna, Italy (12 January 2011)

The eruption began with intermittent bubble explosions with increasing frequency and intensity from the evening of 11 January to 21:40 GMT of 12 January and intermittent fountains from 21:40 to 21:50 GMT (first phase). From 21:50 to 23:15 GMT, a transition to sustained fountains was observed with a peak magma jet height of 800 m and tephra plume height 9 km (second—paroxysmal—phase); a lava flow was also observed in the evening of 12 January. Small intermittent bubble explosions were again observed from 23:15 to 23:30 GMT, and low-intensity effusive activity and irregular low-frequency bubble explosions were observed up to 04:15 GMT (third phase).

Examples of post-eruption descriptions

Montserrat, West Indies (17 September 1996; fully described by Robertson et al. (1998))

On 17 September 1996, the Soufriere Hills Volcano started a period of dome collapse involving about 12 × 10^6 m^3 (DRE) of andesitic lava. A peak plume height of 14–15 km was derived based on the largest pumice clasts (from the model of Carey and Sparks 1986). The height estimate indicates a DRE discharge rate of magma of 4300 m^3 s^{-1} (based on Sparks et al. 1997). Wind speed averaged over plume rise was about 6–8 m s^{-1}. An approximate DRE volume of andesitic tephra fallout of about 3.2 × 10^6 m^3 was derived assuming a peak discharge rate of 4300 m^3 $s^{-1}$and an exponential decay of discharge rate with a decay constant of 12 ± 3 min. Magma water content was of 2.5–5 %. Ejecta consists of moderate (density = 1160 kg m^{-3}) to poorly (density = 1300 to 2000 kg m^{-3}) vesicular juveniles, dense non-vesicular glassy clasts (density = 2600 kg m^{-3}), breccias cut by tuffisite veins and hydrothermally altered lithics (mean density = 2480 kg m^{-3}). A maximum launch velocity of 180 m s^{-1} is estimated for 1.2-m diameter dense blocks ejected to 2.1-km distance by using projectile models (Fagents and Wilson 1993; Bower and Woods 1996). Based on plume height and magma discharge rate, the explosive eruption can be classified as small-moderate to sub-Plinian based on plume height and MER according to Bonadonna and Costa (2013).

Etna, Italy (12 January 2011—paroxysmal phase; fully described by Calvari et al. (2011), Andronico et al. (2014a) and Viccaro et al. (2015))

Sustained fountains of potassic trachybasaltic magma occurred between 21:50 to 23:15 GMT on 12 January 2011 that were associated with a peak magma jet height of 800 m, a tephra plume height 9 km and the emplacement of a lava flow. A mass of erupted tephra fallout of 1.5 ± 0.4 × 10^8 kg was derived averaging values obtained from the method of Pyle (1989), Fierstein and Nathenson (1992), Bonadonna and Houghton (2005) and Bonadonna and Costa (2012) (without considering the cone fraction), and a MER of 2.5 ± 0.7 × 10^4 kg s^{-1} was obtained dividing the erupted mass by the duration of the paroxysmal phase (100 min). The total grain size distribution peaked at −3 ϕ with a range between −5 and 5 ϕ was derived applying the Voronoi Tessellation of Bonadonna and Houghton (2005). Winds were blowing with almost constant direction from the NNE and intensity of 16, 15, 86 and 95 knots, at 3, 5, 7 and 9 km a.s.l. (http://weather.uwyo.edu/). It was classified as violent Strombolian based on Walker (1973) and small-moderate based on plume height and MER according to Bonadonna and Costa (2013).

Vesuvius, Italy (plinian phase of the AD 79 Pompeii eruption; fully described by Carey and Sigurdsson (1987) and Cioni et al. (1992, 1995, 1999))

The tephra-fallout deposit associated with the AD 79 Pompeii eruption consists of two main units, compositionally zoned and south-easterly dispersed, intercalated with PDC deposits in proximal areas. Deposit density for both units is 490 kg m^{-3} in proximal area (<20 km, Mdphi < −2) and 1020 kg m^{-3} in distal area (>20 km, Mdphi > −1). A polymodal cumulative total grain size distribution was derived based on the integration of isomass maps of individual size categories and on the method of crystal concentration of Walker (1980). Mode values of individual grain size populations are −2.8, −0.8 and 5 ϕ, respectively.

White pumice fallout: simple, massive, reversely graded, bearing accidental lithic fragments (mainly limestone and marbles) from the volcano basement and cognate lithics (mainly lava) (wt% lithics averaged over the whole deposit = 10.3). Magma composition = K-phonolite; 10–15 vol% phenocrysts; peak plume height = 26 km (based on the method of Carey and Sparks 1986); MER = 8×10^7 kg s^{-1} (derived from plume height applying the model of Sparks 1986); tephra volume = 1.1 km^3 (applying the method of Fierstein and Nathenson 1992); wind direction = N145; wind speed = 28 m s^{-1} (based on the method of Carey and Sparks 1986); maximum measured thickness = 120 cm at 10 km from vent. Classified as Plinian based on the diagram of Walker (1973).

Grey pumice fallout: simple stratified pumice-rich deposit with four ash-bearing, plane to cross laminated, PDC beds interlayered (wt% lithics averaged over the whole deposit = 11.8). Magma composition = K-tephritic phonolite; 16–20 vol% phenocrysts; peak plume height = 32 km (based on the method of Carey and Sparks 1986); MER = 1.5×10^8 kg s^{-1} (derived from plume height applying the model of Sparks (1986)), tephra volume = 1.8 km^3 (applying the method of Fierstein and Nathenson 1992); wind direction = N145; wind speed = 31 m s^{-1} (based on the method of Carey and Sparks 1986); max measured thickness = 160 cm at 10 km from vent. Classified as Plinian based on the diagram of Walker (1973).

References

1. Andronico D, Cristaldi A, Scollo S (2008) The 4-5 September 2007 lava fountain at south-east crater of Mt Etna, Italy. J Volcanol Geotherm Res 173(3–4):325–328CrossRefGoogle Scholar

2. Andronico D, Scollo S, Cristaldi A, Lo Castro D (2014a) Representivity of incompletely sampled fall deposits in estimating eruption source parameters: a test using the 12–13 January 2011 lava fountain deposit from Mt. Etna volcano, Italy, Bullettin of Volcanology 76:861. doi: 10.1007/s00445-014-0861-3Google Scholar

3. Andronico D, Scollo S, Lo Castro MD, Cristaldi A, Lodato L, Taddeucci J (2014b) Eruption dynamics and tephra dispersal from the 24 November 2006 paroxysm at south-east crater, Mt Etna, Italy. J Volcanol Geotherm Res 274:78–91. doi: 10.1016/j.jvolgeores.2014.01.009CrossRefGoogle Scholar

4. Bonadonna C, Costa A (2012) Estimating the volume of tephra deposits: a new simple strategy. Geology 40(5):415–418CrossRefGoogle Scholar

5. Bonadonna C, Costa A (2013) Plume height, volume and classification of volcanic eruptions based on the Weibull function. Bull Volcanol 75(742). doi: 10.1007/s00445-013-0742-1

6. Bonadonna C, Houghton BF (2005) Total grainsize distribution and volume of tephra-fall deposits. Bull Volcanol 67:441–456CrossRefGoogle Scholar

7. Bower SM, Woods AW (1996) On the dispersal of clasts from volcanic craters during small explosive eruptions. J Volcanol Geotherm Res 73(1–2):19–32CrossRefGoogle Scholar

8. Calvari S, Salerno GG, Spampinato L, Gouhier M, La Spina A, Pecora E, Harris AJL, Labazuy P, Biale E, Boschi E (2011) An unloading foam model to constrain Etna’s 11–13 January 2011 lava fountaining episode. J Geophys Res 116:B11207. doi: 10.1029/2011JB008407CrossRefGoogle Scholar

9. Carey S, Sigurdsson H (1987) Temporal variations in column height and magma discharge rate during the 79 ad eruption of Vesuvius. Geol Soc Am Bull 99(2):303–314CrossRefGoogle Scholar

10. Carey SN, Sparks RSJ (1986) Quantitative models of the fallout and dispersal of tephra from volcanic eruption columns. Bull Volcanol 48:109–125CrossRefGoogle Scholar

11. Cas RAF, Wright JV (1988) Volcanic successions, modern and ancient: a geological approach to processes, products, and successions. Allen & Unwin, London/Boston, p 528Google Scholar

12. Castruccio A, Clavero J, Segura A, Samaniego P, Roche O, Le Pennec JL, Droguett B (2016) Eruptive parameters and dynamics of the April 2015 sub-Plinian eruptions of Calbuco volcano (southern Chile). Bull Volcanol 78(9):62. doi: 10.1007/s00445-016-1058-8

13. Cioni R, Marianelli P, Sbrana A (1992) Dynamics of the AD 79 eruption: stratigraphic, sedimentological and geochemical data on the successions from the Somma-Vesuvius southern and eastern sectors. Acta Vulcanol 2:109–123Google Scholar

14. Cioni R, Civetta L, Marianelli P, Metrich N, Santacroce R, Sbrana A (1995) Compositional layering and syn-eruptive mixing of a periodically refilled shallow magma chamber—the ad-79 plinian eruption of Vesuvius. J Petrol 36(3):739–776CrossRefGoogle Scholar

15. Cioni R, Santacroce R, Sbrana A (1999) Pyroclastic deposits as a guide for reconstructing the multi-stage evolution of the Somma-Vesuvius caldera. Bull Volcanol 61(4):207–222CrossRefGoogle Scholar

16. Collini E, Soledad Osores M, Folch A, Viramonte JG, Villarosa G, Salmuni G (2013) Volcanic ash forecast during the June 2011 Cordon Caulle eruption. Nat Hazards 66(2):389–412Google Scholar

17. Colucci S, de'Michieli Vitturi M, Neri A, Palladino D (2014) An integrated model of magma chamber, conduit, and column for the analysis of sustained magmatic eruptions. Earth Planet Sci Lett 404:98–110CrossRefGoogle Scholar

18. Costa A, Sparks RSJ, Macedonio G, Melnik O (2009) Effects of wall-rock elasticity on magma flow in dykes during explosive eruptions. Earth Planetary Science Letters 288:455–462CrossRefGoogle Scholar

19. Costa A, Gottsmann J, Melnik O, Sparks RSJ (2011) A stress-controlled mechanism for the intensity of very large magnitude explosive eruptions. Earth Planetary Science Letters 310:161–166CrossRefGoogle Scholar

20. de' Michieli Vitturi M, Clarke AB, Neri A, Voight B (2013) Extrusion cycles during dome-building eruptions. Earth Planet Sci Lett 371-372:37–48CrossRefGoogle Scholar

21. Fagents SA, Wilson L (1993) Explosive volcanic-eruptions. 7. The ranges of pyroclasts ejected in transient volcanic explosions. Geophys J Int 113(2):359–370CrossRefGoogle Scholar

22. Fierstein J, Nathenson M (1992) Another look at the calculation of tephra volumes. Bull Volcanol 54:156–167CrossRefGoogle Scholar

23. Francis P (1993) Volcanoes: a planetary perspective. Clarendon Press, Oxford, p 443Google Scholar

24. Francis PW, Glaze LS, Pieri D, Oppenheimer CMM, Rothery DA (1990) Eruption terms. Nature 346Google Scholar

25. Garces M (2013) On infrasound standards, part 1: time, frequency, and energy scaling. InfraMatics 2:13–35. doi: 10.4236/inframatics.2013.22002CrossRefGoogle Scholar

26. Gèze B (1964) Sur la classification des dynamismes volcaniques. Bull Volcanol 27:237–257CrossRefGoogle Scholar

27. Harris AJL, Flynn LP, Keszthelyi L, Mouginis-Mark PJ, Rowland SK, Resing JA (1998) Calculation of lava effusion rates from Landsat TM data. Bull Volcanol 60(1):52–71CrossRefGoogle Scholar

28. Hedervari P (1963) On the energy and magnitude of volcanic eruptions. Bull Volcanol 25:373–385CrossRefGoogle Scholar

29. Houghton BF, Gonnermann HM (2008) Basaltic explosive volcanism: constraints from deposits and models. Chemie Der Erde-Geochemistry 68(2):117–140CrossRefGoogle Scholar

30. Houghton BF, Swanson DA, Rausch J, Carey RJ, Fagents SA (2013) Pushing the volcanic explosivity index to its limit and beyond: constraints from exceptionally weak explosive eruptions at Kīlauea in 2008. Geology 41:627–630. doi: 10.1130/G34146.1

31. Houghton BF, Carey RJ, Rosenberg MD (2014) The 1800a Taupo eruption: “ill wind” blows the ultraplinian type event down to plinian. Geology. doi: 10.1130/G35400.1Google Scholar

32. Koyaguchi T, Suzuki YJ, Kozono T (2010) Effects of the crater on eruption column dynamics. J Geophys Res 115:B07205. doi: 10.1029/2009JB007146CrossRefGoogle Scholar

33. Lacroix A (1908) La Montagne Pelee Apres Ses Eruptions. Kessinger Publishing, Whitefish, p 146Google Scholar

34. Marchetti E, Harris AJL (2008) Trends in activity at Pu’u ‘O’o during 2001-2003: insights from the continuous thermal record. Geological Society London Special Publications 307:85–101. doi: 10.1144/SP307.6CrossRefGoogle Scholar

35. McDonald A (1972) Volcanoes. Prentice-Hall Inc., Englewood Cliffs, p 510Google Scholar

36. Mercalli G (1907) I vulcani attivi della terra: morfologia - dinamismo - prodotti - distribuzione geografica – cause. Ulrico Hoepli, Milan, p. 421Google Scholar

37. Newhall CG, Self S (1982) The volcanic explosivity index (Vei)—an estimate of explosive magnitude for historical volcanism. Journal of Geophysical Research-Oceans and Atmospheres 87(NC2):1231–1238CrossRefGoogle Scholar

38. Perret FA (1950) Volcanological observations. Carnegie Institution of Washington, Publication 549, Washington DC, p. 162Google Scholar

39. Pioli L, Azzopardi BJ, Cashman KV (2009) Controls on the explosivity of scoria cone eruptions: magma segregation at conduit junctions. J Volcanol Geotherm Res 186(3–4):407–415CrossRefGoogle Scholar

40. Pyle DM (1989) The thickness, volume and grainsize of tephra fall deposits. Bull Volcanol 51(1):1–15CrossRefGoogle Scholar

41. Rittmann A (1944) Vulcani attività e genesi. Editrice Politecnica, NaplesGoogle Scholar

42. Rittmann A (1962) Volcanoes and their activity. Wiley-Interscience Publishers, New York, p. 305Google Scholar

43. Robertson R, Cole P, Sparks RSJ, Harford C, Lejeune AM, McGuire WJ, Miller AD, Murphy MD, Norton G, Stevens NF, Young SR (1998) The explosive eruption of Soufrière Hills volcano, Montserrat, West Indies, 17 September, 1996. Geophys Res Lett 25(18):3429–3432CrossRefGoogle Scholar

44. Rosi M, Vezzoli L, Castelmenzano A, Grieco, G (1999) Plinian pumice fall deposit of the Campanian Ignimbrite eruption (Phlegraean Fields, Italy). J Volcanol Geotherm Res 91:179–198Google Scholar

45. Sapper K (1927) Vulkankunde. J Engelhorns Nachf, Stuttgart, p. 424Google Scholar

46. Self S, Sparks RSJ (1978) Characteristics of pyroclastic deposits formed by the interaction of silicic magma and water. Bull Volcanol 41:196–212CrossRefGoogle Scholar

47. Siebert L, Simkin T, Kimberly P (2010) Volcanoes of the world. University of California Press, BerkeleyGoogle Scholar

48. Sonder (1937) Zur Theorie und Klassifikation der eruptiven vulkanischen Vorgänge. Geol Rundschau 27:499–458CrossRefGoogle Scholar

49. Sparks RSJ (1986) The dimensions and dynamics of volcanic eruption colums. Bull Volcanol 48:3–15CrossRefGoogle Scholar

50. Sparks RSJ, Bursik MI, Carey SN, Gilbert JS, Glaze LS, Sigurdsson H, Woods AW (1997) Volcanic Plumes. John Wiley & Sons, Chichester, p. 574Google Scholar

51. Thorarinsson S (1944) Petrokronologista Studier pa Island. Geographes Annuales Stockholm 26:1–217Google Scholar

52. Valentine GA, Gregg TKP (2008) Continental basaltic volcanoes—processes and problems. J Volcanol Geotherm Res 177(4):857–873CrossRefGoogle Scholar

53. Viccaro M, Calcagno R, Garozzo I, Giuffrida M, Nicotra E (2015) Continuous magma recharge at Mt. Etna during the 2011–2013 period controls the style of volcanic activity and compositions of erupted lavas. Miner Petrol 109:67–83. doi: 10.1007/s00710-014-0352-4CrossRefGoogle Scholar

54. Vidal CM, Komorowski JC, Métrich N, Pratomo I, Kartadinata N, Prambada O, Michel A, Carazzo G, Lavigne F, Rodysill J (2015) Dynamics of the major plinian eruption of Samalas in 1257 AD (Lombok, Indonesia). Bull Volcanol 77(9):1–24CrossRefGoogle Scholar

55. Walker GPL (1973) Explosive volcanic eruptions—a new classification scheme. Geol Rundsch 62:431–446CrossRefGoogle Scholar

56. Walker GPL (1980) The Taupo pumice: product of the most powerful known (ultraplinian) eruption? J Volcanol Geotherm Res 8:69–94CrossRefGoogle Scholar

57. Williams H, McBirney AR (1979) Volcanology. Freeman, Cooper, San Francisco, CA, p. 397Google Scholar

58. Woods A, Bokhove O, De Boer A, Hill B (2006) Compressible magma flow in a two-dimensional elastic-walled dike. Earth Planet Sci Lett 246(3–4):241–250CrossRefGoogle Scholar

59. Wright JV, Smith AL, Self S (1980) A working terminology of pyroclastic deposits. J Volcanol Geotherm Res 8(2–4):315–336CrossRefGoogle Scholar

60. Yokoyama I (1956) Energetics in active volcanoes. 1st paper (activity of volcano Mihara, Ooshima Island during the period 1953-54). Tokyo University Earthquake Research Institute Bulleting 34:185–196Google Scholar

61. Yokoyama I (1957a) Energetics in active volcanoes. 2nd paper. Tokyo University Earthquake Research Institute Bulleting 35:75–97Google Scholar

62. Yokoyama I (1957b) Energetics in active volcanoes. 3rd paper. Tokyo University Earthquake Research Institute Bulleting 35:99–107Google Scholar