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MeMoVolc report on classification and dynamics of volcanic explosive eruptions

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Abstract

Classifications of volcanic eruptions were first introduced in the early 20th 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 characterised 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

25 **1. Introduction**

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

49 dynamics. Of concern is that limitations in our ability to categorize and classify eruptions may
50 hinder our progress in understanding eruptions and communication of hazards.

51 Early studies of physical volcanology, and proposals of classification schemes, were mainly
52 based on visual observations of eruptive phenomena at specific volcanoes, and eventually
53 evolved to take into account deposit quantification (e.g. Mercalli 1907; Lacroix 1908; McDonald
54 1972; Williams and McBirney 1979; Walker 1973). In practice, due to its nearly ubiquitous
55 presence in the different eruptive styles, tephra fallout is traditionally the main type of deposit
56 investigated in order to provide insights into the eruptive dynamics (here tephra is considered in
57 the sense of Thorarinsson (1944), i.e. collective term used to describe all particles ejected from
58 volcanoes irrespective of size, shape and composition). However, by considering only the
59 dispersal of tephra, and not, for example, the deposits' internal stratigraphy, the complex and
60 unsteady source dynamics typical of small-moderate explosive eruptions cannot yet be fully
61 captured *post facto* from the deposits. Many eruptions show hybrid features, starting with one
62 eruptive style but terminating with another, resulting in a complex stratigraphic record that is
63 difficult to classify. Yet, other eruptions have characteristics that are gradational between the
64 defined eruptive styles, such as Strombolian and Vulcanian, reflecting transitions in physical
65 phenomena that are as yet imperfectly understood and quantified. Some eruptions would be
66 better described based on the analysis of all volcanic products (e.g. volume ratio between
67 erupted lava and tephra, or volume ratio between fallout and pyroclastic density currents
68 deposits), and especially of the products related to those phases of the eruption marking a shift
69 in the eruptive style. Importantly, ignimbrite-forming eruptions, which include some of the
70 largest on Earth, cannot be simply classified by our present schemes. Furthermore, when dealing
71 with deposits from the rock record, there is often large uncertainty in associating a time-scale
72 with the internal stratigraphy, so that layering and stratification could be related to changes of

73 dynamics during a rather continuous event but also to quite distinct eruptive pulses (e.g. 1707
74 eruption of Fuji volcano, Japan).

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

88 A comprehensive approach to the description of explosive volcanic eruptions can only result
89 from the combined efforts of many scientists working in various sub-disciplines. A
90 multidisciplinary group of the international volcanological community gathered at the University
91 of Geneva on 29-31 January 2014 under the sponsorship of the MeMoVolc Research Networking
92 Programme of the European Science Foundation and the Department of Earth Sciences of the
93 University of Geneva in order to: i) review existing classification schemes and discuss the needs
94 of eruption classification; ii) fill the gap between recent advances in geophysical, modelling and
95 field strategies and current classification schemes; iii) investigate how the contributions from
96 different sub-disciplines can be combined. Specific objectives were to: i) review new advances in
97 our mechanistic understanding of a broad range of eruptive styles and their relation to eruption

98 classification; ii) identify the critical parameters that drive and characterize explosive volcanism
99 of different types; iii) determine the main processes that control the temporal evolution of
100 eruptions, and the frequently observed changes in eruptive style; iv) select research priorities
101 that could allow new advances in the characterization, understanding and classification of
102 volcanic eruptions; v) suggest a roadmap for producing a rational and comprehensive
103 classification scheme. This consensual document attempts to summarize the outcome of two
104 and a half days of talks, posters, break-out sessions, and plenary discussions (see also the
105 workshop website for Program details: [http://www.unige.ch/hazards/MeMoVolc-
106 Workshop.html](http://www.unige.ch/hazards/MeMoVolc-Workshop.html)).

107

108 **2. Main general classification schemes used to characterize volcanic eruptions**

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

116 The first general classification schemes of volcanic eruptions identified “type volcanoes”,
117 made associations with specific eruptive features, were mostly qualitative, and were biased
118 towards the more frequent small to moderate eruptions (e.g. Mercalli 1907; Lacroix 1908;
119 Sapper 1927; Perret 1950). They were eventually replaced by schemes based on processes and
120 quantitative descriptions, with special focus on the characteristics of tephra deposits (e.g.
121 Walker 1973, 1980; Self and Sparks 1978; Wright et al. 1980). Five parameters were introduced
122 for estimating the scale of explosive eruptions (e.g. Walker 1973): i) magnitude (volume of

123 erupted material typically converted to Dense Rock Equivalent, DRE); ii) intensity (volume of
124 ejecta per unit time); iii) dispersive power (related to the total area of dispersal and, therefore,
125 to plume height); iv) violence (related to kinetic energy); v) destructive potential (related to the
126 extent of devastation). Eruptive styles (Table 1) were determined based on two parameters: F,
127 fragmentation index (indicator of the explosiveness of the eruption) and D, area of pyroclastic
128 dispersal (indicator of the column height). Specifically, D is the area enclosed by an isopach
129 contour representing 1% of the maximum thickness ($0.01 T_{\max}$) and F is the percent of tephra
130 $<1\text{mm}$, measured along an axis of dispersal where the isopach is 10% of T_{\max} ($0.1 T_{\max}$).
131 Eventually the styles representing violent Strombolian, ash emissions, Vesuvian and the silicic
132 equivalent of surtseyan were discarded and new terms such as phreatoplinian and ultra-Plinian
133 were introduced (Walker 1980; Self and Sparks 1978; Cas and Wright 1988). However, the term
134 violent Strombolian has remained in the literature and has been preferred by Valentine and
135 Gregg (2008) to the new term introduced by Francis et al. (1990) (i.e. microplinian) mostly
136 because of its widespread use and because it does not suggest the injection above the
137 tropopause as does the term Plinian.

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

148 of Bonadonna and Costa (2013)); vii) the usual association between hydromagmatism and ash-
149 dominated eruptions and viii) the absence of hybrid and multi-style eruptions.

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

169 Newhall and Self (1982) introduced a classification strategy that assigned a certain erupted
170 volume and plume height range to the most common eruptive styles: the Volcanic Explosivity
171 Index, VEI. This logarithmic scale ranges from “non-explosive” Hawaiian eruptions (VEI 0; volume
172 <10,000 m³; plume height <100m) to “very large” ultra-Plinian eruptions (VEI 5-8; volume >1

173 km³; plume height > 25 km). This scale is widely used in global databases (e.g. GVP,
174 <http://www.volcano.si.edu>; Siebert et al. 2010) and hazard/risk assessments because it offers a
175 comforting analogue to the more widely used earthquake magnitude scale. The main
176 shortcomings of this approach include: i) the implicit assumption of a link between magnitude
177 and plume height, and, therefore, intensity; ii) a gap between modern eruptions that are
178 typically defined by plume height, versus ancient eruptions that are typically defined by erupted
179 volume; iii) impossibility of classifying effusive (lava) eruptions, which by default are assigned a
180 VEI of 0 or 1; iv) ambiguity in the definition of VEI 0 that covers at least six orders of magnitude
181 of eruptive volume (e.g. Houghton et al. 2013); v) ambiguity in the definition of erupted volume
182 that in the global databases sometimes includes deposits of PDCs (as per the original definition
183 of VEI) and sometimes only tephra-fall deposits; vi) the difficulty of characterizing long-lasting
184 eruptions associated with multiple phases of varying style and intensity; vii) the difficulty of
185 estimating the tephra volume of the cone edifice built during small-moderate eruptions that
186 usually is not considered in the calculation of the total erupted mass (in fact, in this type of
187 eruptions, the volume of the material forming the cone may be several times larger than the
188 mappable medial to distal tephra-fall sheets).

189 Regardless of their shortcomings, some categories have been used by many classification
190 schemes, while others have been abandoned in more recent works (Table 1). It is clear how
191 classification schemes have been simplified with time, trying also to avoid nomenclature based
192 on specific volcanoes (as suggested long ago by Rittmann 1944). Plinian is clearly universally
193 accepted, as it is used in all classification schemes proposed, demonstrating the comparative
194 ease of classifying relatively large eruptions. Hawaiian, Strombolian, Vulcanian, sub-Plinian and
195 ultra-Plinian have also been used by most authors, even though their definitions can be complex
196 and ambiguous. As an example, lava fountains frequently observed in recent years at Etna
197 typically have been characterised by the formation of eruption columns > 2 km above the cone,

198 and so mostly fit in the violent Strombolian to sub-Plinian field of Walker (1973) rather than in
199 the Hawaiian to normal Strombolian spectrum (e.g. Andronico et al. 2014). Finally, even though
200 ultra-Plinian was used by many authors, we consider this category as a special case because it
201 was based on only one eruption (i.e. Taupo 1800a; Walker 1980) and recent evidence shows that
202 the large footprint of this apparently single fallout layer is an artefact of a previously
203 unrecognized shift in the wind field during a fairly complex eruption, rather than indicating
204 extreme eruptive vigour. When the associated deposit is subdivided into subunits, the Taupo
205 eruption is better classified as Plinian (Houghton et al. 2014). Additional field evidence for
206 possible ultra-Plinian deposits has been recently published for the 1257AD Samalas eruptions
207 (Lombok, Indonesia; Vidal et al. 2015). Separate from specific examples, but in accord with the
208 Bonadonna and Costa (2013) classification, the upper limit of ultra-Plinian eruptions can be
209 defined on the basis of MER, based on the conditions for column collapse (i.e. greater than $\sim 10^9$
210 kg s^{-1} ; e.g. Koyaguchi et al. 2010).

211

212 **3. Critical processes and parameters that drive and characterize explosive volcanism of** 213 **different types**

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

219 **4. Research priorities**

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

222 Conduit processes and dynamics

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

231 Abrupt transitions in eruption regime

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

239 Unsteadiness

240 Many eruptions are characterized by unsteadiness, involving fluctuations of eruption intensity
241 on a wide range of length scales and time scales (sub-second to hours or days). For example, the
242 scale of unsteadiness (periodicity and amplitude of fluctuations) increases when passing from
243 Plinian (quasi-steady), through sub-Plinian (oscillating, sustained, short-lived column), to violent
244 Strombolian (lava fountain-fed, discontinuous, pulsating column) to Vulcanian (discrete
245 explosions separated by pauses). Unsteadiness should be quantified with continuous

246 measurements of MER, plume height and meteorological conditions at the highest possible
247 resolution, or with indirect measurements of tephra bedding and grain-size variations (in
248 particular for post-eruption analysis).

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

- 250 - How do we define unsteadiness (e.g. cyclic vs. irregular pulsating activity; steady, quasi-
251 steady or highly unsteady)?
- 252 - How do we quantify unsteadiness (e.g., could we quantify unsteadiness using measurements
253 of plume/jet height, geophysical observations and/or gas emissions? How can unsteadiness
254 be characterized in a deposit)?
- 255 - How do we distinguish between source-generated unsteadiness related to eruptive
256 fluctuation at the vent and process-generated unsteadiness generated for example by
257 changes in wind direction and speed (e.g., Houghton et al. 2014)?
- 258 - What are the causes of unsteadiness (e.g., ascent rate too low to sustain gas supply; ascent
259 rate too low to keep pace with discharge; transition from open to closed system degassing;
260 magma-water interaction; syn-eruptive changes in magma rheology or magma permeability
261 able to modulate magma discharge; interaction with country rock; interaction with the
262 atmosphere; unsteady dynamics of the column; unsteady sedimentation processes due to
263 local instabilities)?
- 264 - What are the relevant time scales for unsteadiness? Which timescales can be measured and
265 quantified? Can the characteristic timescale of conduit processes be defined and compared
266 with the characteristic time of plume ascent?

267 Eruption energy and energy balance

268 The possibility of defining eruptive styles in terms of energy balance (partitioning between
269 thermal, kinetics, fragmentation energy) and energy flux (rather than total energy) has been
270 identified as a potential alternative to classifications based on erupted mass and plume height

271 but requires further investigation (e.g. Yokoyama 1956; 1957a,b; Hedervari 1963; Garces 2013).
272 It is not yet practical to derive energy from deposits of past eruptions.

273 **5. Objectives of eruption classification**

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

286 **6. A roadmap for a more comprehensive approach to eruption classification**

287 Shortcomings of current systems of classification, in particular associated with the small-
288 moderate eruptions and the diversity of phenomena that can occur within a single event (e.g.
289 PDCs, lava), can be addressed by making these systems adaptable to multiple levels of detail and
290 multi-parameter space, particularly including unsteadiness and duration. In fact, it maybe be
291 useful to describe volcanic eruptions using a qualitative classification with numerical information
292 (i.e. an eruption descriptor plus numerical information) following an “event-tree” approach.
293 From the identification and analysis of common features using this kind of categorization we
294 may find a way to classify rationally a spectrum of eruption styles using a minimal number of

295 descriptors. Critical parameters include: deposit geometry, dispersal, plume height, eruption
296 duration, mass associated with each phenomenon, grain-size, presence of unsteadiness, types
297 and characteristics of juvenile material, abundance of wall-rock fragments.

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

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

314 **7. Concluding remarks and open questions**

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

- 319 1) All existing classification schemes fail to collate all volcanic eruptions in one simple
320 diagrammatic form, and do not account for all volcanic behaviours and products. In addition,
321 we identified that eruption categories used by most schemes include: Hawaiian, Strombolian,
322 Vulcanian, sub-Plinian, Plinian and ultra-Plinian. There is a need for the community as a whole
323 to work collectively towards improved classification of eruptions and their deposits.
- 324 2) The main parameters and processes characterizing volcanic eruptions include: initial
325 conditions, conduit-related magma dynamics, and external factors (see Table 2).
- 326 3) Classification schemes need to be objective, focused and designed for specific goals (e.g.
327 scientific understanding, hazard/risk assessment, communication with the public, civil
328 defence institutions and the scientific community) and sufficiently clear and simple to
329 promote accurate transfer of knowledge and scientific exchange.
- 330 4) Classification should be based on clearly defined observables, and aimed at identifying the
331 main processes. We found that most existing classification schemes are based on processes
332 (e.g. Walker 1973, 1980; Pyle 1989; Bonadonna and Costa 2013) but the parameters do not
333 capture all relevant volcanic phenomena and are too broad to distinguish between transient
334 versus sustained eruptions or steady versus unsteady behaviours.
- 335 5) Classification schemes should be comprehensive and encompass a variety of eruptive styles
336 and volcanic products, including for example, lava flows, PDCs, gas emissions and cinder cone
337 or caldera formation. While we have focussed on subaerial eruptions, classification should
338 extend to submarine eruptions.
- 339 6) Real-time classifications should be based on quantitative observations of phenomena (Table
340 3), whereas post-eruption classifications should be based on the quantification of volcanic
341 products and deposit-derived parameters (Table 4). Both real-time and post-eruption
342 descriptions should include uncertainty estimates. When possible, real-time and post-

343 eruption descriptions should be integrated because they often provide different and
344 complementary information.

345 7) Currently we do not have a system that can be used for all eruptions. It might be possible in
346 the future to have a more comprehensive classification scheme, but it is likely that it will be
347 associated with a different way of measuring eruptions (e.g. energy balance) instead of
348 evolving from existing schemes.

349 8) None of the existing schemes consider the distinction between steady and unsteady
350 processes. We identified that unsteadiness is, in fact, a key factor for describing volcanic
351 eruptions, but also concluded that we do not yet have effective means of classifying
352 unsteadiness itself. Future eruption classification schemes should incorporate the concept of
353 unsteadiness.

354 9) Classification schemes should also describe eruption duration to distinguish between short-
355 lived and long-lasting eruptions (e.g. Calbuco 2015, Chile versus Cordón Caulle 2011, Chile).

356 10) Open questions, processes and parameters that need to be addressed and better
357 characterised in order to develop more comprehensive classification schemes and to progress
358 in our understanding of volcanic eruptions include: conduit processes and dynamics, and of
359 abrupt transitions in eruption regime, unsteadiness, eruption energy, and energy balance.

360 Finally, we note the advice of Williams and McBirney (1979) who recognised that, even though
361 some specific nomenclature to classify volcanic eruptions is poorly defined, it has become too
362 firmly entrenched in volcanological literature to abandon. The best improvements are to define
363 old terms more clearly, and introduce new ones only when necessary. As a result, we envisage
364 that a future classification scheme will retain some existing terms, but will need to better define
365 them based on the parameters we identify for the classification of eruptions in real time and for
366 post-eruption classification (Tables 3 and 4). Based on the frequency of use (Table 1), we expect

367 terms such as Hawaiian, Strombolian, Vulcanian, sub-Plinian, Plinian and ultra-Plinian to be part
368 of future classification, but we suggest that they be combined with a phenomenological and
369 quantitative description (possibly including uncertainty estimates), such as that reported in
370 Appendix A, which provides key parameters including: i) plume/jet height, duration, MER,
371 erupted mass/volume, energy, exit velocity, gas flux and composition, atmospheric conditions
372 and unsteadiness *for real-time classification* and ii) thickness and maximum clast size
373 distribution, deposit density, deposit componentry, shapes of juvenile clasts, deposit layering,
374 pyroclast composition/crystallinity, erupted mass/volume of different volcanic products, total
375 grain-size distribution, plume height, MER, duration, exit velocity, and wind direction and speed
376 *for post-eruption classification*. In addition, information to identify magma/water interaction and
377 quantify componentry should be provided together with the key parameters listed above. We
378 also conclude that a few additional eruption categories might need to be added, because some
379 eruptions cannot be described by the five most commonly used categories identified in Table 1,
380 e.g. non-explosive, phreatic, continuous ash emissions /ash venting.

381

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386 that improved the final manuscript.

387

Examples of descriptions and classifications of volcanic eruptions

390 Eruption classification needs to be fit-for-purpose (e.g. scientific understanding, hazard/risk
391 assessment, communication with public, civil defence institutions and scientific community) and
392 clear and simple enough to promote accurate transfer of knowledge and scientific exchange. It
393 might vary depending on whether the classification is based on direct observations (i.e. real
394 time) or on volcanic deposits (i.e. post eruption). In particular, in real time, classification should
395 be based on quantitative observations of phenomena (Table 3), while, for post-eruption
396 descriptions, classification should be based on the quantification of volcanic products and
397 deposit-derived parameters (Table 4). Here we present some concrete examples developed by
398 workshop participants. For two eruptions (i.e., Montserrat, 17th September 1996; Etna, 12th
399 January 2011) we provide both types of descriptions (real time and post-eruption).

A.1 Examples of real-time descriptions***A.1.1 Gas Piston event at Pu'u 'O'o, Hawaii (23rd February 2002)***

402 Basaltic lava flow from vent at foot of Pu'u 'O'o south wall begins at 19:59 and extends 100 m
403 east by 20:15 (5 m wide proximally). A bulk volume flow rate of $0.26 \text{ m}^3 \text{ s}^{-1}$ for the lava flow was
404 derived based on an emplacement duration of 16 minutes, which can be converted into a MER
405 value of $414 \pm 219 \text{ kg s}^{-1}$ using the vesicle corrected density of Harris et al. (1998) (i.e. 1590 ± 840
406 kg m^{-3}). Continuous spattering at vent was observed throughout emplacement. Spattering
407 transits to bubble bursts at 20:41. Bursts increase in frequency to more than 1 per second by
408 20:45. At 20:45 bubble bursting and lava emission terminated by onset of gas jet with loud roar
409 to 25(?) m. Waning gas jet until 20:15. Vertical blue gas jet with few diffuse, small (cm-sized)
410 incandescent particles. Spatter-bubble-jet cycle recommences; next jet at 21:16. It was classified
411 as gas piston event type "c" according to Marchetti and Harris (2008). Gas flux was not
412 measured.

413 **A.1.2 Montserrat, West Indies (17th September 1996)**

414 A major phase of lava dome collapse began at 11:30 am on the 17 September 1996, continued
415 for 9 hours and waned after 8:30 pm. The explosive eruption began at 11:42 pm and had
416 finished by 00:30 am on 18 September. Seismic energy on the RSAM record peaked at about
417 midnight and then declined exponentially. A vertical plume was intercepted by a commercial jet
418 at 11.3 km, which is associated with a Dense Rock Equivalent (DRE) discharge rate of magma of
419 $1300 \text{ m}^3 \text{ s}^{-1}$ (based on Sparks et al. 1997). Assuming a constant discharge rate over the whole 48-
420 minute duration, a DRE volume of about $3.7 \times 10^6 \text{ m}^3$ was obtained. From weather satellite
421 images (Satellite Analysis Branch of NOAA/NESDIS) plume transport was both to the west and to
422 the east by regional trade and antitrade winds with a maximum speed at tropopause of 17 m s^{-1} .
423 Pumice and lithic lapilli fell widely across southern Montserrat. Classified as small-moderate
424 based on plume height and MER according to Bonadonna and Costa (2013).

425 **A.1.3 Etna, Italy (12th January 2011)**

426 The eruption began with intermittent bubble explosions with increasing frequency and intensity
427 from the evening of 11th January to 21:40 GMT of 12th January and intermittent fountains from
428 21:40 to 21:50 GMT (first phase). From 21:50 to 23:15 GMT a transition to sustained fountains
429 was observed with a peak magma jet height of 800 m and tephra plume height 9 km (second –
430 paroxysmal- phase); a lava flow was also observed in the evening of 12th January. Small
431 intermittent bubble explosions were again observed from 23:15 to 23:30 GMT and low-intensity
432 effusive activity and irregular low-frequency bubble explosions were observed up to 04:15 GMT
433 (third phase).

434 **A.2 Examples of post-eruption descriptions**

435 **A.2.1 Montserrat, West Indies (17th September 1996)**

436 On 17 September 1996 the Soufriere Hills Volcano started a period of dome collapse involving
437 about $12 \times 10^6 \text{ m}^3$ (DRE) of andesitic lava. A peak plume height of 14-15 km was derived based

438 on the largest pumice clasts (from the model of Carey and Sparks 1986). The height estimate
439 indicates a DRE discharge rate of magma of $4300 \text{ m}^3 \text{ s}^{-1}$ (based on Sparks et al. 1997). Wind
440 speed averaged over plume rise was about $6\text{-}8 \text{ m s}^{-1}$. An approximate DRE volume of andesitic
441 tephra of about $3.2 \times 10^6 \text{ m}^3$ was derived assuming a peak discharge rate of $4300 \text{ m}^3 \text{ s}^{-1}$ and an
442 exponential decay of discharge rate with a decay constant of 12 ± 3 minutes. Magma water
443 content was of 2.5-5%. Ejecta consists of moderate (density = 1160 kg m^{-3}) to poorly (density =
444 1300 to 2000 kg m^{-3}) vesicular juveniles, dense non-vesicular glassy clasts (density = 2600 kg m^{-3}),
445 breccias cut by tuffisite veins and hydrothermally altered lithics (mean density = 2480 kg m^{-3}).
446 A maximum launch velocity of 180 m s^{-1} is estimated for 1.2 m diameter dense blocks ejected to
447 2.1 km distance using projectile models (Fagents and Wilson, 1993; Bower and Woods, 1996).
448 Based on plume height and magma discharge rate, the explosive eruption can be classified as
449 small-moderate to sub-Plinian based on plume height and MER according to Bonadonna and
450 Costa (2013).

451 *More details in Robertson et al. (1998)*

452 **A.2.2 Etna, Italy (12th January 2011 – paroxysmal phase)**

453 Sustained fountains of potassic trachybasaltic magma occurred between 21:50 to 23:15 GMT on
454 12th January 2011 that were associated with a peak magma jet height of 800 m, a tephra plume
455 height 9 km and the emplacement of a lava flow. A mass of erupted tephra of $1.5 \pm 0.4 \times 10^8 \text{ kg}$
456 was derived averaging values obtained from the method of Pyle (1989), Fierstein and Nathenson
457 (1992), Bonadonna and Houghton (2005) and Bonadonna and Costa (2012) (without considering
458 the cone fraction) and a MER of $2.5 \pm 0.7 \times 10^4 \text{ kg s}^{-1}$ was obtained dividing the erupted mass by
459 the duration of the paroxysmal phase (100 minutes). The total grain-size distribution peaked at -
460 3ϕ with a range between -5 and 5ϕ was derived applying the Voronoi Tessellation of
461 Bonadonna and Houghton (2005). Winds were blowing with almost constant direction from the
462 NNE and intensity of 16, 15, 86, and 95 knots, at 3, 5, 7, and 9 km a.s.l.

463 (<http://weather.uwyo.edu/>). It was classified as violent Strombolian based on Walker (1973) and
464 small-moderate based on plume height and MER according to Bonadonna and Costa (2013).
465 *More details in Calvari et al. (2011), Andronico et al. (2014) and Viccaro et al. (2015)*

466 **A.2.3 Vesuvius, Italy (Plinian phase of the AD 79 Pompeii eruption)**

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

474 *White pumice fallout:* simple, massive, reversely graded, bearing accidental lithic fragments
475 (mainly limestone and marbles) from the volcano basement, and cognate lithics (mainly lava)
476 (wt% lithics averaged over the whole deposit=10.3). Magma composition= K-phonolite; 10-15
477 vol% phenocrysts; peak plume height= 26 km (based on the method of Carey and Sparks 1986);
478 MER=8x10⁷ kg s⁻¹ (derived from plume height applying the model of Sparks 1986); tephra
479 volume=1.1 km³ (applying the method of Fierstein and Nathenson 1992); wind direction= N145;
480 wind speed=28 m s⁻¹ (based on the method of Carey and Sparks 1986); maximum measured
481 thickness= 120 cm at 10 km from vent. Classified as Plinian based on the diagram of Walker
482 (1973).

483 *Grey pumice fallout:* simple stratified pumice-rich deposit with four ash-bearing, plane to
484 cross laminated, PDC beds interlayered (wt% lithics averaged over the whole deposit=11.8).
485 Magma composition= K-tephritic phonolite; 16-20%vol phenocrysts; peak plume height= 32 km
486 (based on the method of Carey and Sparks 1986); MER=1.5x10⁸ kg s⁻¹ (derived from plume
487 height applying the model of Sparks (1986)), tephra volume=1.8 km³ (applying the method of

488 Fierstein and Nathenson 1992); wind direction= N145; wind speed=31 m s⁻¹ (based on the
489 method of Carey and Sparks 1986); max measured thickness= 160 cm at 10 km from vent.
490 Classified as Plinian based on the diagram of Walker (1973).
491 *More details in Carey and Sigurdsson (1987) and Cioni et al. (1992; 1995; 1999)*

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626

627 **Table captions**

628

629 **Table 1.** Categories used to classify explosive volcanic eruptions as reported in main “general”
630 classification schemes (the most used categories are highlighted in grey).

631 McDonald (1972) is adjusted from Mercalli (1907), Lacroix (1908) and Sapper (1927); Williams and
632 McBirney (1979) is a simplification of Mercalli (1907), Sonder (1937), Rittmann (1962), Gèze (1964)
633 and Walker (1973); Francis (1990*) indicates Francis et al. (1990).

634

635 **Table 2.** Main processes and parameters characterizing volcanic explosive eruptions

636

637 **Table 3.** Relevant parameters to be described in real-time analysis (observation/monitoring based)
638 and to be possibly associated with uncertainty estimates.

639

640 **Table 4.** Relevant parameters to be described in post-eruption analysis (deposit based) and to be
641 possibly associated with uncertainty estimates. Derived parameters are estimated based on
642 dedicated models.

Table 1

	Macdonald (1972)	Walker (1973, 1980)	Williams & McBirney (1979)	Newhall & Self (1982)	Pyle (1989)	Francis (1990*, 1993)	Valentine & Gregg (2008)	Bonadonna & Costa (2013)
Lava lake						✓		
Basaltic flood	✓							
Hawaiian	✓	✓	✓	✓		✓	✓	
Strombolian	✓	✓	✓	✓	✓	✓	✓	
Violent Strombolian	✓	✓					✓	Small- Moderate
Microplinian						✓ Violent Stromb.		
Strombolian paroxysm	✓							
Vulcanian	✓	✓ Vesuvian	✓	✓		✓		
Peléean	✓ variety of Vulcanian		✓			✓		
subplinian		✓			✓	✓ Vesuvian		
Plinian	✓ variety of Vulcanian	✓	✓ Krakatoan	✓	✓	✓		✓
Ultraplinian		✓		✓	✓	✓		✓
Rhyolitic flood	✓							
Ash emission		✓ conduit clearing						
Ultravulcanian	✓ no magma							
Gas eruption	✓ no magma							
Fumarolic	✓ no magma							
Phreatic			✓ steam blast	✓				
Surtseyan		✓			✓	✓		
Phreato- magmatic			✓ including Surtseyan					
PhreatoPlinian		✓				✓		
Shallow submarine eruptions	✓							
Subglacial						✓		

<i>Initial conditions</i>
<ol style="list-style-type: none"> 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
<i>Conduit magma dynamics</i>
<ol style="list-style-type: none"> 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)
<i>Eruptive processes and parameters</i>
<ol style="list-style-type: none"> 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 time scale) 18. Plume height, temperature, density and collapse conditions 19. Partitioning of mass into plume, pyroclastic density currents and lava flows
<i>External factors</i>
<ol style="list-style-type: none"> 20. Atmospheric conditions (e.g., wind direction and speed, air entrainment, humidity, temperature, density) 21. Magma/water-ice interaction 22. Crustal stress/earthquakes 23. Thermo-mechanical interaction with country rock (including country rock entrainment and conduit wall collapse) 24. Caldera collapse timing, mechanism and extent

Table 3

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 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 (revised)

Erupted volume/mass of different volcanic products	derived (from deposits)
Plume height	derived (from tephra 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, cristallinity and density of juvenile clasts	Measured on selected clasts
Unsteadiness	derived (from bedding/grading)
Wind direction and speed	derived (from tephra deposits)
Magma composition	measured on selected clasts
Magma rheology	measured or derived from data on composition and cristallinity