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# 1 **Eruption type probability and eruption source parameters at Cotopaxi and** 2 **Guagua Pichincha volcanoes (Ecuador) with uncertainty quantification**

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## 60 **Competing interests**

61 The authors have no competing interests to declare.

## 62 **Code and data availability**

63 The EXCALIBUR code used to process the data is downloadable at the following address  
64 <http://www.lighttwist.net/wp/excalibur>. Other scripts to process the data are available under request – i.e. ERF  
65 scores, logic tree probability calculations, Monte Carlo sampling. The raw data used in this study are available as  
66 supplementary material and in a repository from the Figshare community with the following DOI  
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## 68 **Authors’ contributions**

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81 Editing.

## 82 **Abstract**

83 **Abstract**  
84 Future occurrence of explosive eruptive activity at Cotopaxi and Guagua Pichincha volcanoes, Ecuador, is  
85 assessed probabilistically, utilizing expert elicitation. Eight eruption types were considered for each volcano.  
86 Type event probabilities were evaluated for the next eruption at each volcano and for at least one of each type  
87 within the next 100 years. For each type, we elicited relevant eruption source parameters (duration, average  
88 plume height and total tephra mass). We investigated the robustness of these elicited evaluations by deriving  
89 probability uncertainties using three expert scoring methods. For Cotopaxi, we considered both rhyolitic and  
90 andesitic magmas. Elicitation findings indicate that the most probable next eruption type is an andesitic  
91 hydrovolcanic/ash-emission (~26-44% median probability), which has also the highest median probability of  
92 recurring over the next 100 years. However, for the next eruption at Cotopaxi, the average joint probabilities for  
93 sub-Plinian or Plinian type eruption is of order 30-40% - a significant chance of a violent explosive event. It is  
94 inferred that any Cotopaxi rhyolitic eruption could involve a longer duration and greater erupted mass than an  
95 andesitic event, likely producing a prolonged emergency. For Guagua Pichincha, future eruption types are  
96 expected to be andesitic/dacitic, and a vulcanian event is judged most probable for the next eruption (median  
97 probability ~40–55%); this type is expected to be most frequent over the next 100 years, too. However, there is a  
98 substantial probability (possibly >40% in average) that the next eruption could be sub-Plinian or Plinian, with all  
99 that implies for hazard levels.

100

101 **Keywords**: Cotopaxi volcano, Guagua Pichincha volcano, volcanic hazard, elicitation, uncertainty  
102 quantification

103

## 1. Introduction

The future behavior of a volcano is a matter of central concern for volcanic hazard and risk assessment. The estimation of probability of eruption scenarios depends on two factors: i) the temporal probability of an eruption and ii) the conditional probability of a particular eruptive scenario given that an eruption occurs (Connor et al. 2015; Poland and Anderson 2020). In this study we will mostly focus on the latter. These probabilities serve as a basis for scenario and evacuation plan definition, long-term urban planning and risk mitigation. Additionally, the estimate of the uncertainty ranges for eruption source parameters (ESPs) is a key aspect for the development of probabilistic hazard maps, which mainly rely on numerical models (e.g., Costa et al. 2009; Bonasia et al. 2011; Biass et al. 2014; Vázquez et al. 2019). To the extent that the past eruptive history of a volcano is known and rigorously analysed, both aspects can be addressed with some measure of accuracy provided associated uncertainties are accounted for.

While the recurrence probabilities of different volcanic eruptions can be assessed through the development of temporal models (e.g., Mulargia et al. 1985; De la Cruz-Reyna 1993; Bebbington and Cronin 2011; Bevilacqua et al. 2016), conditional probabilities of eruption type are usually described using either Bayesian belief networks (e.g., Aspinall and Woo 2014; Hincks et al. 2014; Christophersen et al. 2018) or event trees (e.g., Newhall and Hoblitt 2002; Martí et al. 2008; Neri et al. 2008; Tierz et al. 2020). Incompleteness and uncertainty of the eruptive records affect temporal modelling, and difficulties in incorporating monitoring signals are challenging issues that have been tackled using several approaches, including hidden Markov models (Aspinall et al. 2006; Wang and Bebbington 2012; Bevilacqua et al. 2020a), variably combined statistical models (Marzocchi and Bebbington 2012; Runge et al. 2014; Bevilacqua et al. 2018) or the failure forecast method (Voight 1988; Robertson and Kilburn 2016; Kilburn 2018; Bevilacqua et al. 2019; Bevilacqua et al. 2020b; Bevilacqua et al. 2020c).

Each eruption of a volcano is characterized by specific ESPs whose range of variation, especially if they are factors to be applied in probabilistic studies, can be estimated from field data (e.g. Macedonio et al. 2016; Parra et al. 2016; Biass et al. 2017) or derived from analogue volcanoes and/or general distribution of ESPs (e.g. Mastin et al. 2009; Sheldrake 2014; Sheldrake et al. 2016; Gouhier et al. 2019). While it is straightforward to define a uniform probability distribution between two end-member values for each ESP, this approach can entail potential loss of information that might be present in data and records, which may provide an objective basis for a more informative uncertainty distribution function. To offset such limitations, it can be useful to adopt structured expert judgment techniques (Aspinall 2006; Aspinall and Cooke 2013) to explicitly derive a unique credible uncertainty range and a corresponding elemental probability distribution for each of the investigated variables through weighted pooling of a group of experts' uncertainty distributions. This approach has been adopted both for describing the future behavior of a volcano (Martí et al. 2008; Neri et al. 2008) and also for determining some ESPs (Bebbington et al. 2018; Christophersen et al. 2018; Aspinall et al. 2019).

The aim of this paper is to report assessed conditional probabilities of experiencing different eruption types (and their main ESPs) - conditional on the future occurrence of an eruption - at Cotopaxi and Guagua Pichincha volcanoes, two of the most active and hazardous volcanoes in Ecuador. At both volcanoes, the spectrum and magnitudes of potential eruptive types can range from minor but long-lasting ash emissions or vulcanian to Plinian eruptions, and their relative probabilities of occurrence must be assessed on a coherent basis to obtain self-consistent volcanic hazards assessments and to support reasoned decision-making. In this paper we are focusing on explosive eruptions due to the greater hazard that they pose in terms of the large areas potentially affected by tephra dispersal.

Here, these challenges are addressed with an established expert elicitation methodology for the formal numerical quantification of uncertainties, the results of which can inform event trees for the two volcanoes. These findings contribute to a long-term project aimed at developing new probabilistic tephra hazard maps for Cotopaxi and Guagua Pichincha volcanoes. In this project, a new procedure for quantifying relevant uncertainties in a tephra transport and dispersal model has been recently proposed (Tadini et al. 2020). Here, the quantification of other, related uncertainties (both epistemic and aleatoric, Tadini et al. 2017b) represents a further advance towards a fully probabilistic volcanic hazard assessment approach that will enable uncertainties to be explicitly accounted for producing the resulting tephra hazard maps.

For Cotopaxi, two studies have been recently published about tephra fallout hazard and risk assessment. Biass and Bonadonna (2013) developed semi-probabilistic and probabilistic hazard maps and curves by using the TEPHRA2 model (Bonadonna et al. 2005) and considering eruptive scenarios with  $VEI \geq 3$ . Moreover, using data from the global volcanism program database, the authors calculated the probability of occurrence of an eruption of  $VEI \geq 3$  for the next 10 (36.2%) and 100 (98.9%) years. Additionally, Biass et al. (2013) performed a risk assessment for eruptions with  $VEI \geq 4$ , highlighting the possible collapse due to ash loading of several thousands of houses in the proximity of the volcano, the destruction of agriculture and the possible disruption of major roads. The potential high impact of tephra fallout on the new Quito International airport, considering Cotopaxi among other volcanoes, has been addressed by Volentik and Houghton (2015). For Guagua Pichincha,

164 they highlighted that the small-size AD 1999 eruption (see section 2.2) resulted in huge economic losses to the  
165 tourism and agricultural sectors. In order to consider further the impact that an eruption of even moderate size  
166 could have on aviation, the definitions of eruptive scenarios and recurrence probabilities for Cotopaxi and  
167 Guagua Pichincha are therefore crucial.

168 Before addressing these and other hazard-related assessment issues, we provide first a general overview on  
169 Cotopaxi and Guagua Pichincha volcanoes (section 2) and on expert elicitation techniques (section 3, with  
170 details in the Appendix). Then, we present a detailed analysis of our findings (section 4), with further  
171 considerations about the procedure and prospective implications for hazard levels at Cotopaxi and Guagua  
172 Pichincha (section 5).

## 173 2. Volcanic context

174  
175 Cotopaxi and Guagua Pichincha volcanoes (Fig. 1) are located, respectively, ~60 km South and ~10 km  
176 West of Quito, Ecuador's capital city. About 150,000 and 2 million inhabitants live within 30 km of Cotopaxi  
177 and Guagua Pichincha volcanoes (Global Volcanism Program 2013), respectively.  
178

### 179 2.1 Cotopaxi volcano

180 Cotopaxi is a 5,897 m high active volcano located on the Eastern Cordillera. According to Hall and Mothes  
181 (2008), the eruptive history of Cotopaxi volcano started roughly 0.5 Ma, and it is characterized by a bimodal  
182 volcanism involving rhyolitic (70–75 wt.% SiO<sub>2</sub>) and andesitic (56–62 wt.% SiO<sub>2</sub>) magmas. The same authors  
183 calculated a total erupted DRE volume during the last 0.5 Ma of 28.54 km<sup>3</sup> and they gave a detailed evolution of  
184 total erupted volume with time (Fig. 20 of Hall and Mothes 2008). Cotopaxi activity was characterized during its  
185 early stages by a series of large eruptions involving magmas of rhyolitic composition lasting ~0.1 Ma (Barrancas  
186 series, Hall and Mothes 2008). After a long repose period of ~0.4 Ma, except for a short andesitic activity at  
187 around 0.45 Ma BP (Rio Pita Series), the volcanic activity resumed with other five eruptive episodes (F series,  
188 Hall and Mothes 2008). Such series (9.6–5.5 ka BP) were mainly rhyolitic in composition, but andesitic magmas  
189 erupted repeatedly, a fact that allowed Hall and Mothes (2008) to infer that andesitic magma already existed or  
190 was rising from depth. The subsequent Colorado Canyon series (~4.5 ka) involved rhyolitic magmas and  
191 included a sector collapse on the NE side of Cotopaxi (Smyth and Clapperton 1986; Mothes et al. 1998; Vezzoli  
192 et al. 2017). From the end of the Colorado Canyon episode until the present day, magmas erupted from Cotopaxi  
193 were almost all andesitic in composition, except one rhyolitic ash level dated at 2.1 ka (Barberi et al. 1995; Hall  
194 and Mothes 2008). For the period 4–1 ka, Hall and Mothes (2008) reported a total of 25 eruptions (18 of which  
195 were considered as Plinian events with VEI 4). The subsequent period represented the historical activity of  
196 Cotopaxi volcano, which lasted from AD 1532–34 up to AD 1880, with minor activity occurring in the 20<sup>th</sup>  
197 century (Pistolesi et al. 2011) and a full resumption of activity with the AD 2015 eruption (Bernard et al. 2016;  
198 Hidalgo et al. 2018). The period 1532–1880 (total erupted volume of 2.14 DRE km<sup>3</sup>, Hall and Mothes 2008) was  
199 studied in detail by Pistolesi et al. (2011) who identified 13 layers/eruptions grouped in 6 sets. Within the last 1  
200 ky, all the eruptions involved andesitic magmas and there have been both violent Strombolian VEI 2–3 (AD  
201 1853), sub-Plinian VEI 3–4 (AD 1877 and XVIII century) and Plinian VEI 4–5 (Layer 3 - 820±80 years BP;  
202 Layer 5 - 1180± 80 years BP, Biass and Bonadonna 2011; Tsunematsu and Bonadonna 2015) eruptions. After  
203 small-scale (VEI 1–2) explosions reported in the years 1904 and 1942 (Pistolesi et al. 2011), Cotopaxi  
204 reawakened in AD 2015 resulting in a ~3 months long eruption, characterized by an opening hydrovolcanic (or  
205 phreatomagmatic) phase (Bernard et al. 2016) followed by a long-lasting ash emission (Gaunt et al. 2016;  
206 Hidalgo et al. 2018). Table 1 summarizes the main typologies of explosive eruptions of Cotopaxi considered in  
207 the production of the logic trees in the following sections. We highlight that this table does not record completely  
208 the eruptive history of the volcano, but it has been used as a basis to describe the spectrum of explosive activity  
209 at Cotopaxi volcano. Despite this explosive activity is preponderant, effusive activity at Cotopaxi is also  
210 documented (Hall and Mothes 2008; Pistolesi et al. 2011), although it is often linked to other explosive eruptions  
211 (e.g. AD 1853; Pistolesi et al. 2011). For this reason, a separate category of “effusive eruption” has not been  
212 considered in our study.  
213

### 214 2.2 Guagua Pichincha volcano

215 The Pichincha volcanic complex is composed of two distinct edifices sitting atop the El Cinto lavas (0.1–1.1  
216 Ma, Robin et al. 2010), the older Rucu Pichincha (4,694 m a.s.l.) and the younger Guagua Pichincha (4,784 m  
217 a.s.l.). The magmatic composition of the erupted products of both the Rucu and Guagua Pichincha is andesitic to  
218 dacitic (55–66 wt.% SiO<sub>2</sub>), while the eruptive history of the former spans the period 0.85 Ma–0.15 Ma and the  
219 second began to erupt at around 60 ka (Robin et al. 2010). The development of the Guagua Pichincha volcano

220 involved two major sector collapses (at ~11 ka and ~4 ka), which were linked to changes in the erupted rock  
221 chemistry due to the arrival of new magma batches (Robin et al. 2010). The last “Toaza” sector collapse  
222 occurred around 4 ka and the volcanic activity resumed roughly 2 ka with the development of a new summit  
223 dome (the “Cristal dome”). This dome experienced phases of growth /collapse and related block-and-ash flows  
224 and blasts (Robin et al. 2008). Due to the above-mentioned changes in rock chemistry that occurred after the  
225 “Toaza” sector collapse, we will focus on the eruptive history after 4 ka. The volcanic activity of the last 2000  
226 years has been the topic of several studies aimed at better characterizing the stratigraphy, the chronology of the  
227 eruptions and the volcanic hazard (Geotermica Italiana 1989; Barberi et al. 1992; Robin et al. 2008). This period  
228 involved three major eruptive cycles (I century, X century, Historic) separated by repose periods of the order of  
229 300–500 years. Each cycle was initiated with phases of dome emplacement and explosive episodes, and involved  
230 a final Plinian-like eruption (Robin et al. 2008). As a reference, the Historic cycle involved at least 3 eruptive  
231 explosive episodes (testified by historical accounts, Wolf 1904) in AD 1566, 1575, and 1582, with ash fallout in  
232 Quito and pyroclastic density currents at the west side of the volcano. The Plinian-like eruption of AD 1660  
233 closed this cycle (Robin et al. 2008). After the Historic cycle, phreatic explosions occurred at Guagua Pichincha  
234 in the XIX century and became more frequent (and correlated with seasonal rain) in the years 1981-1998  
235 (Garcia-Aristizabal et al. 2007). Particularly, in AD 1998 there was a sudden increase of the phreatic activity,  
236 which presaged the first dome-forming eruption of the 1999-2001 cycle. During this cycle, 8 dome-forming  
237 eruptions (each of them followed by the dismantling of the newly formed dome) took place, and several  
238 Vulcanian eruptions (including the AD 1999, the largest of the cycle) destroyed the first domes (Garcia-  
239 Aristizabal et al. 2007; Wright et al. 2007). The similarities (in terms of eruptive styles) between the eruptive  
240 cycle of 1999-2001 with the early stages of the Historic and X century cycles, permitted Robin et al. (2008) to  
241 infer that the 1999-2001 cycle might be the first step of a mid-term evolution that will eventually result in a  
242 Plinian-like eruption like that of AD 1660. Table 2 summarizes the main typologies of explosive eruptions of  
243 Guagua Pichincha volcano considered in the production of the logic trees in the following sections. Also in this  
244 case we report in this table just a selection of eruptions to define the typologies for the logic trees in Fig. 2. For  
245 Guagua Pichincha, differently from Cotopaxi, the effusive dome-forming activity is more significant, but it is not  
246 considered in our study due to the specific focus on explosive activity.  
247

### 248 **3. Methods**

249

#### 250 *3.1 Elicitation*

251 Our study involved all the participants in the author list, representing different levels of experience and  
252 a variety of scientific backgrounds. These specialists all have at least a basic background in volcanology, and the  
253 majority has undertaken detailed work on Cotopaxi or Guagua Pichincha volcanoes, or both. The elicitation (see  
254 Appendix A for details) started with a seed questionnaire (for determining experts’ weighting) composed of 15  
255 factual questions about Ecuadorian/South American volcanism and numerical modelling of volcanic ash  
256 (without considering monitoring data). Participants were not expected to know precisely the quantitative values  
257 of the questions but they were expected to be able to provide credible intervals that captured the ‘true’ values for  
258 at least some of the questions. Thus, for each question, participants were asked to provide their immediate  
259 uncertainty judgments by suggesting their own 5<sup>th</sup> percentile, 50<sup>th</sup> percentile (median), and 95<sup>th</sup> percentile  
260 estimates of the – for them, unknown - values in question. To avoid influencing and group-thinking, each person  
261 responded individually and confidentially to the elicitation facilitator. The seed questionnaire used in this session  
262 is provided as Online Resource 1.

263 These questions were processed by applying three well-established scoring methods to calculate each  
264 expert’s calibration and informativeness scores (details are available in the Appendix A). The methods are  
265 Cooke’s Classical Model (CM - Cooke 1991; Aspinall 2006), the Expected Relative Frequency method (ERF -  
266 Flandoli et al. 2011; Bevilacqua 2016), and the Equal Weights (EW) rule (Bevilacqua 2016). The purpose of  
267 using three scoring methods is twofold. First, it underlines the robustness of the outcomes where CM, ERF and  
268 EW methods have similar or coincident trends. Second, it can help identifying if two or more different “school  
269 of thoughts” exist among the experts on any item of interest. A discussion about the outcomes of the three  
270 scoring methods (CM, ERF and EW) is given in Flandoli et al. (2011) and reported in Appendix A.

271 The calibration and informativeness scores are thus used to define each expert’s weight to be applied when  
272 considering the judgments on the ‘target item’ questions, i.e. the variables of interest. In this form, target item  
273 responses are pooled together with the experts’ weights to produce a group synthesized uncertainty distribution,  
274 often called a ‘decision maker’ solution (DM). Where necessary for clarity in the paper, we will also call  
275 “decision-taker” the actual person in charge of taking decisions. As with the calibration questions, for the target  
276 questions the experts were asked again to provide their judgments and associated uncertainties as 5<sup>th</sup> percentile,  
277 50<sup>th</sup> percentile (median), and 95<sup>th</sup> percentile values. The advantage of this approach (especially for ESPs) is that

278 it is possible to obtain elemental uncertainty distribution markers for each variable and not just simple variation  
279 ranges between a maximum and minimum value.

280 The purpose of the target questionnaires about Cotopaxi and Guagua Pichincha was twofold. Firstly, it  
281 aimed at assessing the relative conditional probability of different types of volcanic activity (see Appendix A for  
282 the definition of “eruption” used in this study) and associated magma composition (the latter for Cotopaxi only)  
283 in a specific temporal frame. More specifically, such questions were considered in two frameworks, namely the  
284 “next eruption” and the “next 100 years” cases, the former being the most explosive phase of the eruption  
285 considered and the latter being the probability of having at least one eruption type/magma composition within  
286 the next 100 years. We introduced this differentiation because the ‘next eruption’ case is surely the most relevant  
287 for short to medium-term hazard assessment, but that would have to be updated with new expert judgments and  
288 re-evaluated after a new eruption would occur. On the contrary, the ‘next 100 years’ case aims at providing a  
289 longer time frame and it facilitated the experts in focusing on single eruptions in such time frame. These two sets  
290 of questions are denoted, respectively, with the abbreviations “NE” and “N100” in the following sections. An  
291 important consequence of this subdivision is that, while the NE case contains mutually exclusive events  
292 summing to 100%, the N100 case does not exclude the possibility of having eruptions of different type as  
293 subsequent events.

294 Figure 2 displays the logic tree for Cotopaxi and Guagua Pichincha, whose branches represent the above-  
295 mentioned target questions. With these event trees we aim at quantifying the conditional probability of explosive  
296 eruptions, as they pose a higher number of hazards than effusive ones. The latter should be considered as part of  
297 the “Other eruption” types, which include both effusive events and other events not recorded in the stratigraphy  
298 of the volcano nor in the historical observations. However, we do not exclude that for some other type of  
299 eruptions (for example the “Violent Strombolian” or “Vulcanian” for Cotopaxi and Guagua Pichincha,  
300 respectively) there may be some lava outpourings associated to the eruption scenario.

301 The probability of occurrence of the various types of volcanic activity could be also inferred from the  
302 available information on past recurrence rates in the global datasets of volcanic eruptions (Smithsonian GVP,  
303 LaMEVE). Statistical modeling of global VEI-frequency distributions using extreme value methods (Coles and  
304 Sparks 2006; Deligne et al. 2010; Furlan 2010; Rougier et al. 2016; Papale 2018), or through comparison of the  
305 global record with the well-characterized record in Japan (Kiyosugi et al. 2015) provide insight into possible  
306 corrected distributions, but regional differences make the global record difficult to apply to single volcanoes  
307 (Rougier et al. 2018). Much remains to be learned about global trends in volcanic explosivity, and uncertainty is  
308 very high (Deligne et al. 2017). In particular, there are problems with calculation of VEI distribution through  
309 time, including under-recording of small magnitude events backward through time, and over-recording of VEI 2  
310 events by the Smithsonian GVP. For these latter reasons, our expert judgment approach does not rely on such  
311 global data.

312 The target questionnaires addressed also the uncertainty range of some key ESPs (eruption duration in  
313 minutes, total mass of the tephra fallout deposit in  $10^9$  kg and average plume height in km) for the different types  
314 of eruptions, according their importance for volcanic hazard assessment and numerical modelling, especially  
315 concerning tephra fallout.

316 We have not directly elicited some other parameters important for tephra fallout hazard assessment and  
317 numerical modeling, such as total grain-size distribution, particle densities, particle shape factors, and initial  
318 volatile content of magma. For these parameters we have considered that either their uncertainty has been  
319 already adequately modeled without using expert judgment techniques (e.g. total grain-size distribution, Costa et  
320 al. 2016) or that their uncertainty range might be better described by a linear variation between two end-  
321 members. For example, in this latter case, we found good constraints for both Cotopaxi and Guagua Pichincha  
322 volcanoes for initial water mass fractions (Wright et al. 2007; Samaniego et al. 2010; Andújar et al. 2017; Martel  
323 et al. 2018), particle densities (Bonadonna and Phillips 2003; Pistolesi et al. 2011) and particle shape factors  
324 (Riley et al. 2003).

## 325 4. Results

326

### 327 4.1 Eruption probabilities and ESPs

328 In this section, we report the results of the elicitation, subdivided in graphical outputs (Figs. 3 and 4) and  
329 triplets of values (Tables 3-6). The graphical outputs show the probability density functions of the DM resulting  
330 from the application of a Gaussian kernel density estimator (Silverman 1986; Connor and Connor 2009; Tadini  
331 et al. 2017a) to the weighted combination of the experts’ probability distribution judgments. This means that we  
332 extracted a sufficient number of samples ( $10^5$ ) of expert answers, a number selected by iteration to assure a  
333 robust convergence of the kernel density estimator. This differs from the original formulation of the ERF method  
334 (Flandoli et al. 2011), in which the DM resulted from the linear combination of the quantiles of the experts’  
335 probability distributions. In particular, we abandoned the quantile combination approach because it would have

336 averaged the median values of different experts instead of producing multimodal distributions (e.g. Bevilacqua,  
337 2016). More specifically, when calculating the DMs, we performed a linear combination (i.e. a probability  
338 mixture) of maximum entropy distributions, i.e. uniformly distributed between the elicited percentiles (Cooke,  
339 1991) in all the three methods. We remark that in the calculation of the ERF scores on the ‘seed questionnaire’  
340 we adopted triangular probability distributions, while for the definition of the DM on the ‘target questionnaire’  
341 we used maximum entropy distributions. This choice enabled a better comparison of ERF with the CM and EW,  
342 but it differs from Bevilacqua et al. (2015) and Tadini et al. (2017a).

343 We also highlight that multi- or bimodality in the resulting probability density functions is a consequence  
344 of the different modes expressed by different experts, while the full uncertainty range (in Tables 3-6) is obtained  
345 from the envelope of all experts and their judgments. The triplets of values in the tables therefore summarize the  
346 DM’s probability distribution with three percentiles (5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup>). These triplets have been recalculated  
347 from the original elicitation data in order to have conditional probabilities with respect to rhyolitic or andesitic  
348 magmas, respectively. Given the large amount of elicitation data, we only report in the main text the graphical  
349 outputs of the conditional probabilities. Those of the ESPs are provided in the supplementary material (Online  
350 resource 2), together with the experts’ weights (Online resource 3).

351 For Cotopaxi volcano, the results of the elicitation are provided in Figure 3, Table 3 (conditional  
352 probabilities) and Table 5 (ESPs) for the CM, ERF and EW methods. Similarly, for Guagua Pichincha volcano,  
353 results are provided in Figure 4, Table 4 (conditional probabilities) and Table 6 (ESPs). Eruption durations are  
354 given in minutes. We highlight two general observations. Firstly, for all the distributions, in our formulation, the  
355 ERF answers are generally between the CM and the EW ones, and they are significantly closer to the latter; this  
356 is particularly evident by comparing the probability density functions (see Figs. 3 and 4). Secondly, if the  
357 uncertainty range of the distributions is considered (i.e. the 5<sup>th</sup> and 95<sup>th</sup> percentiles in Tables 3, 4, 5 and 6), the  
358 CM distributions are in general more informative, that is, they are more focused (although slightly) around the  
359 50<sup>th</sup> percentile.

360 For Cotopaxi, considering the CM method, we evaluated that the three percentiles (5<sup>th</sup>, 50<sup>th</sup>, 95<sup>th</sup>) of the  
361 conditional probability that the next eruption (NE case) will involve rhyolitic magma are [0.4, 8.4, 39] %, with a  
362 mean value of 13%. The ERF and EW methods produced median values of 11 - 12% and mean values of 16 -  
363 20%. In contrast, the conditional probability of having eruptions involving andesitic magmas is [61, 92, >99] %,   
364 with a mean value of 87% considering the CM method. In these two cases, the corresponding probability density  
365 functions for all the scoring methods (Fig. 3) show a clear unimodality, with the CM scoring method having a  
366 slightly higher peak with respect to ERF and EW. Instead, in the rhyolitic case, the probability density functions  
367 for the sub-Plinian and Plinian eruptions are markedly multimodal for all the scoring methods, with the ERF and  
368 EW solutions having similar trends. The different probability peaks are illustrated in Figure 3. In the andesitic  
369 case, the hydrovolcanic/continuous ash emission (like AD 2015) has been evaluated the most probable next  
370 eruption (NE case). There are, however, some differences among the scoring methods, with the ERF and the EW  
371 having noticeably lower median values (28% and 26%) than the CM solution (44%) – (mean values of 28%,  
372 27%, and 44% respectively). Similar inferences can be made for the corresponding probabilities in the N100  
373 case at Cotopaxi, with probability values that are generally higher because we did not assume mutually exclusive  
374 events. For example, the median probability of at least one hydrovolcanic/continuous ash emission in the next  
375 100 years is 43 - 55%, depending on the method (mean values in 43 - 51%). We remark that the above-  
376 mentioned cases for the NE case, where distributions show bi- or multimodality, have bi- or multimodality also  
377 in the N100 case, with even more fluctuations (see Fig. 3).

378 For the NE case at Guagua Pichincha, despite the fewer number of eruption types (and just one magma  
379 composition in consideration), there is one eruption type (i.e. Vulcanian – see Table 4 and Fig. 4) for which there  
380 are relatively large differences among the scoring methods. A Vulcanian eruption has been considered the most  
381 probable event, but the median values are 55% for the CM, 45% for the ERF and 40% for the EW (mean values  
382 of 51%, 44%, and 40%). More details about the other percentiles can be found in Table 4 and in Appendix B.  
383 The differences among the three scoring methods is, in contrast, lower for the other cases (sub-Plinian, Plinian  
384 and other – Fig. 4). We remark also that the median conditional probability for “Other” eruption types has been  
385 evaluated with a median probability ranging from 7.5% up to 11%, depending on the method selected (mean  
386 values of 13% up to 18%). For the N100 case, considerations similar to those for Cotopaxi can be made as there  
387 are larger fluctuations in the probability density functions (Fig. 4), describing bi- or multimodal distributions for  
388 all cases (except for the “Other eruption” case).

389 Considering parameter uncertainty ranges for both Cotopaxi and Guagua Pichincha (Tables 5 and 6), the  
390 average plume height is the parameter for which the differences among the three scoring methods are lowest (see  
391 also Online resource 2). In general, however, differences between the median values of the other two parameters  
392 (total mass and total duration) for the three scoring methods are generally low.

## 393 4.2 Sensitivity of variable weights to expert group composition

394 Three sensitivity assessments of the outcomes of the CM analysis were performed with respect to experts'  
395 career ages, main scientific expertise and geographic affiliation at the time of the elicitation. The goal was to  
396 highlight possible trends that might have been influenced by the different backgrounds/experiences of the  
397 various experts involved. It is important to highlight that, with respect to any of the sub-groups, the CM  
398 outcomes are not a measure of the average knowledge of the participants of a sub-group about the volcanological  
399 problem as a whole, but rather a measure of the participants' abilities to judge volcanological quantitative  
400 uncertainties. Weights assigned with the EW rule are reported as well in order to highlight the overall agreement  
401 or disagreement among experts within different sub-groups. Six sub-groups were analyzed as paired  
402 comparisons, which are: Senior researchers vs. Early-career researchers (A1 vs. A2 – 14 and 6 experts  
403 respectively); Geologists vs. Mathematicians-Modelers (B1 vs. B2 – 9 and 11 experts respectively) and  
404 Clermont-Ferrand vs. Quito (C1 vs. C2 – 12 and 8 experts respectively). The latter group refers to the location of  
405 the experts at the time of the elicitation, which was performed in one single session, but with experts remotely  
406 connected from the two different localities. Senior researchers were those with > 10 years of academic career  
407 after obtaining the PhD. The pairs of sub-groups (e.g. A1/A2 vs. B1/B2) are significantly different and not  
408 correlated by construction. Therefore, the elicitation responses have been analyzed in order to highlight possible  
409 biases given by the fact that, within the sub-group C1, some experts have not worked on the studied volcanoes as  
410 deeply as those of sub-group C2. The complete dataset for this analysis is available in Online resources 6 and 7.

411 To compare the outputs of the elicitation considering the whole group or different sub-groups, we have  
412 analyzed the outputs in the two tables in Supporting Information by performing principal component analysis  
413 (PCA) of the data (Wold et al. 1987; Chiasera and Cortés 2011). This procedure allowed us to obtain the PCA  
414 eigenvector and its eigenvalues (described by two dimensions' x and y referred here as Dim1 and Dim2), which  
415 indicate the direction of maximum spread of multivariate data. As shown in Figure 5, we used CM data to create  
416 sub-plots with normalized eigenvectors for two sub-groups (A1 vs. A2, B1 vs. B2, C1 vs. C2), along with that of  
417 the whole group (All). This approach allows us to discuss, for each sub-plot, how similar the absolute values,  
418 obtained considering the group as a whole (All), are to one sub-group or another.

419 We remark that in Fig. 5 the direction of each arrow could vary as a function of the uncertainty spread of  
420 the DM solution for each subgroup, and that if the arrow of one subgroup is closer to the reference "All" arrow,  
421 this indicates that the two are more closely similar to each other than the DM solution of the other subgroup.  
422 Conversely, equidistance of the "All" arrow from both subgroups indicates that the "All" DM is balanced  
423 between them.

424 Results displayed in Figure 5 highlight the following trends: i) eigenvectors of the sub-groups for Cotopaxi  
425 (Fig. 5a) tend to have an higher spread, within each sub-plot, than those of Guagua Pichincha (Fig. 5b), as  
426 indicated by the higher percentages of Dim2 in all the Cotopaxi sub-plots; ii) eigenvectors of ESPs tend to be  
427 more closely related to their corresponding "All" solutions than those of conditional probabilities for both  
428 volcanoes, with the exception of sub-groups A1 vs. A2 (Senior researchers vs. Early-career researchers); iii) for  
429 both volcanoes, the eigenvector representing the whole group ("All") tends to be placed in the middle of the  
430 sector defined by the eigenvectors C1 vs. C2 (Clermont-Ferrand vs. Quito), while that for A1 vs. A2 (Senior  
431 researchers vs. Early-career researchers) tends to be closer to the eigenvector A1 and that for B1 vs. B2  
432 (Geologists vs. Mathematicians-Modelers) tends to be consistently closer to the eigenvector B1.

433 These analysis findings, and their possible implications, are discussed in more detail in Section 5 below.  
434

## 435 5. Discussion

436

### 437 5.1 Expert scoring methods and sensitivity analyses

438 In this paper we provide a detailed method to analyze an elicitation that addressed future eruption types  
439 and their likelihoods for Cotopaxi and Guagua Pichincha volcanoes. Our approach involves comparisons of  
440 probability density functions from the experts' judgments about eruption probabilities and eruptive parameters  
441 (Tables 3 and 4, Figs. 3 and 4 and Online resource 2). In earlier studies that involved comparison between  
442 different scoring methods (for Campi Flegrei/Vesuvius volcanoes), consistency of elicitation outputs suggested  
443 that the findings were similar among them and robust (Bevilacqua et al. 2015; Tadini et al. 2017a). In this new  
444 study we find the same trend of consistency for the majority of the questions, suggesting again the general  
445 robustness of elicitation outputs. In just two cases a slightly greater intrinsic uncertainty on some of the issues  
446 elicited demonstrated that different results could be obtained when scoring the experts in a different way (e.g.  
447 "Hydrovolcanic/Ash emission eruption – NE " for Cotopaxi, Fig. 3; "Vulcanian eruption - NE " for Guagua  
448 Pichincha – Fig. 4). These differences highlight a general uncertainty in characterizing both the occurrence and  
449 the ESPs of these types of small magnitude eruptions, for which there is not an extended worldwide database and  
450 which might have been more frequent than those recorded in the stratigraphic record. In addition, it is also more



451 difficult to place these eruption types within well-known eruption categories, which are often mostly based on  
452 larger magnitude events (see for example Mastin et al. 2009). More studies are therefore needed in this sense. It  
453 is also important to remind that in this study we have used a classification scheme for eruptions that differs from  
454 the classical VEI scale: this might also explain some differences observed in experts' assessments, which might  
455 give different VEI scale representations within our classes. Furthermore, while not being highly relevant, the  
456 highlighted differences among scoring methods could be taken into consideration if these particular outputs were  
457 to be used for any hazard or risk decision purposes, and in general a choice should be made about which solution  
458 to adopt: that of the CM, the ERF or the EW method. Notwithstanding the CM scoring method has been used  
459 traditionally in many studies, both in volcanology and other fields (Aspinall 2006), the choice about which  
460 outcome to consider is ultimately a responsibility of the (human) decision-taker. With respect to this latter issue,  
461 it is worth keeping in mind that the CM is a "selective" scoring method (due to the properties of the "calibration"  
462 score, see Appendix A) and is therefore efficient in selecting, from a potentially large group of experts, those that  
463 are statistically more accurate in constraining uncertainties. On the other hand, a less "selective" scoring method,  
464 like ERF, gave results similar to that of the EW method, if compared to the CM. This similarity was enhanced by  
465 having used the same DMs definition algorithm in all the methods, except for the difference in the experts'  
466 scores. While in most of the situations performing this selection using the CM scoring method is justified, in  
467 other contexts it can be important for the human decision-taker to consider pooling outcomes derived from the  
468 judgments of the group as a whole (i.e. by considering counterpart EW or ERF DM solutions). In summary,  
469 comparing the outcomes of different scoring methods allows highlighting differences in scientific basis that  
470 might influence expert forecasts. Such differences are related to variation in assessment of incompleteness of the  
471 eruptive record or variations in the different models (scientific, conceptual, or mechanical) assumed by the  
472 experts for providing their judgments. The investigation of the motivations behind the differences between the  
473 experts responses is not the aim of the elicitation session (see Appendix A; Cooke, 1991).

474 To provide more cogency for the choice of one scoring method over another, or to select estimations  
475 obtained from one specific sub-group of experts, we have also performed PCA analysis to explore the relative  
476 information contents of each option. The trends discussed in section 4.2 highlight primarily that, for the two  
477 volcanoes, the experts' judgments are slightly less homogeneous for Cotopaxi than for Guagua Pichincha, as  
478 indicated by the higher Dim2 percentages in all the sub-plots of Figure 5a with respect to those of Figure 5b.  
479 Very likely, this observation could be correlated with the higher complexity of the logic tree of Figure 3  
480 (Cotopaxi) versus Figure 4 (Guagua Pichincha). In other words, the greater number of eruption types and the  
481 potential involvement of two alternative different magmas complicates matters for Cotopaxi compared with  
482 Guagua Pichincha.

483 Moreover, the ESP PCA sub-plots for Cotopaxi have a higher Dim2 value than that of Guagua  
484 Pichincha. This could be linked to the greater difficulty in constraining uncertainty ranges for the ESPs of the  
485 small magnitude eruptions as the hydrovolcanic/continuous ash emission (Bernard et al. 2016) and Violent  
486 Strombolian type eruptions. However, for both volcanoes (especially for the sub-groups B1 vs. B2, and for C1  
487 vs. C2) Dim2 is lower for the sub-plots with ESPs than for the corresponding sub-plots for conditional  
488 probabilities, suggesting a greater uniformity of judgments among sub-groups for ESPs than for conditional  
489 probabilities.

490 Finally, an important aspect is linked to the orientation of the eigenvector of the whole group (All) with  
491 respect to those of the sub-groups. As highlighted in section 4.2, the eigenvector "All" is found to be located in  
492 the middle of the sector defined by the alternate eigenvectors C1 vs. C2, for both Cotopaxi and Guagua  
493 Pichincha. This observation indicates that the final absolute values are equally distant (and therefore balanced)  
494 between the judgments of the two sub-groups with different institutional locations (i.e. Clermont-Ferrand and  
495 Quito). However, for the sub-plots A1 vs. A2 and for B1 vs. B2 in Figure 5, the "All" eigenvectors are generally  
496 closer to A1 (Senior Researchers), and more toward B1 (Geologists) in the latter. These findings suggest that  
497 institutional affiliation did not influence the DM as much as age and background.

## 498 *5.2 Implications for hazard assessment and numerical modelling*

499 The results of the elicitation have implications for hazard assessment, both for conditional probabilities  
500 and the related eruption parameters. Moreover, it is interesting to consider which questions (and related  
501 scenarios) are affected by greater uncertainties, both from the point of view of epistemic uncertainty on eruption  
502 types conditional probability ("Other eruption" cases) and intra-question uncertainty (i.e. the credible interval  
503 distance between the 5<sup>th</sup> and the 95<sup>th</sup> percentiles within each question). The two timeframes chosen (i.e. next  
504 eruption and next 100 years) enable us also to analyze two different perspectives for the volcanoes. Specifically,  
505 in our opinion, the probability density functions of the NE case could be used for preparing a probabilistic hazard  
506 map (or to define emergency plans) for immediate use. This could be accomplished either by considering single  
507 eruptions, or by combining the different maps obtained for different eruption types, weighted by the appropriate  
508 probability of occurrence (Sandri et al. 2016). In this way, it is possible to create a joint probability hazard map,  
509 which encompasses effects arising from any of the eruptions considered in this study, according to their relative

510 weights. In contrast, the N100 case allows considering a longer time frame and the possibility on eruptive  
511 scenarios that are not mutually exclusive. These probabilities could be used for estimating the total cumulative  
512 hazard in the surrounding territory in the next decades.

513  
514 The ESPs for which the uncertainty distributions have been quantified include most of those defined by  
515 Bonadonna et al. (2012, 2016) as those that need to be parametrized for the majority of existing plume and  
516 tephra transport/deposition numerical models. The list defined by Bonadonna et al. (2012, 2016) includes plume  
517 height, eruption mass, mass eruption rate (inferred from total mass and eruption duration), total grain-size  
518 distribution, and the onset and end of an eruption (defining eruption duration). With the exception of total grain-  
519 size distribution (not elicited for the reasons explained in section 3.1), we have therefore provided detailed  
520 uncertainty distributions for such ESPs. These distributions are not simply represented by uniform distributions  
521 between two extreme values, but they are characterized by a triplet of uncertainty values (5<sup>th</sup>, 50<sup>th</sup>, 95<sup>th</sup>  
522 percentiles) and probability density functions obtained by kernel methods. This probabilistic approach is  
523 particularly beneficial if such parameterizations are used as inputs to numerical models for generating hazard  
524 maps, when iterative re-sampling of the elicited ESP distributions can capture epistemic or aleatoric  
525 uncertainties. When possible, the ESPs here defined have been compared with those available from literature. To  
526 this purpose, we compiled a list of well-studied eruptions (classified according to prevalent magma composition,  
527 VEI, eruptive style, total mass of fallout deposit and plume height) in Table C1 from Appendix C. While this list  
528 is limited and reflects the actual availability of detailed data, it however provides a first order comparison to  
529 evaluate the robustness of our estimations.

530 In the following two sub-sections, we discuss separately the implications for hazards at Cotopaxi and at  
531 Guagua Pichincha volcanoes. Concerning the ESPs for both volcanoes, as pointed out in section 4.1, average  
532 plume height has the lowest variability among the alternative scoring methods, likely due to the better  
533 availability of plume height measurements of eruptions with similar magnitudes/intensities, both at the studied  
534 volcanoes and worldwide (Mastin et al. 2009; Gouhier et al. 2019).

### 535 5.2.1 Cotopaxi volcano

536 The responses given by the experts were concordant in general and did not show evidence for “school  
537 of thoughts” when judging relative probabilities for rhyolitic and andesitic eruptions (i.e. the probability density  
538 functions of rhyolitic and andesitic magmas are unimodal for all three scoring methods). However, the high  
539 relative probability that an eruption at Cotopaxi will be andesitic is more pronounced for the NE case (Fig. 3a)  
540 than for the N100 case (Fig. 3b). The conditional probability of a rhyolitic eruption (as highlighted in section  
541 4.1) is substantially lower than that of an andesitic eruption for both the NE and the N100 cases. This reflects the  
542 fact that the last rhyolitic eruption dates back to 2.1 ky BP (see section 2.1). Nevertheless it is very uncertain and  
543 not negligible, ranging from 0.4% to 50%, with a median probability of 8-12% (mean values 13-20%). We  
544 highlight that at Cotopaxi, eruptions involving rhyolitic magmas characterize mostly the early stages of the  
545 eruptive history of the volcano and, generally, deposits from old, low-magnitude eruptions are rarely preserved.  
546 From this point of view, the conditional probabilities assigned in Table 3, including the “Other type” case, reflect  
547 a conservative approach, in which the possibility of the incompleteness of the rhyolitic eruptive record (i.e.  
548 under-recording) is taken into consideration. The Plinian and sub-Plinian eruptions involving rhyolitic magmas  
549 have therefore a summed mean conditional probability (for the next eruption) of 11-14 %, where the range of  
550 different values depends on the method selected. This mean probability is significantly higher for the N100 case  
551 (19-23%). In this respect, the mean possibility of having at least one large-magnitude rhyolitic eruption is not  
552 negligible, and this has an effect on the expected volcanic hazard, as highlighted with their related ESPs (see  
553 below).

554 Considering andesitic eruptions, it is worth commenting on three aspects. First, similarly to rhyolitic  
555 eruptions, the possibility of an under-recording of old, low-magnitude andesitic eruptions could also not be  
556 excluded, considering that, according to Hall and Mothes (2008), andesitic magmas occurred within the F series  
557 (9.6-5.5 ka BP) rhyolitic eruptive episodes (see section 2.1). Second, the summed mean probability of sub-  
558 Plinian and Plinian eruptions involving andesitic magmas for the NE case is 19-27%. Besides exhibiting a  
559 greater difference between the various scoring methods relative to rhyolitic cases, the conditional probability of a  
560 sub-Plinian or Plinian andesitic eruption is significantly higher than that for a rhyolitic eruption of similar size.  
561 This is an important point because, as mentioned earlier, the magma type can have an impact on the potential  
562 hazards (as implied by the different ranges of ESPs). Third, the “hydrovolcanic/continuous ash emission”  
563 eruption type is considered the most probable next eruption, under all scoring methods. This is consistent with  
564 Bernard et al. (2016), who underline that, despite the under-representation of VEI 1-2 eruptions in the geologic  
565 record, such an eruption type could be the most frequent ones at Cotopaxi (see also Wolf 1904). There is,  
566 however, large uncertainty associated with responses on eruption type probabilities, as highlighted by: i) the  
567 largest credible intervals between the 5<sup>th</sup> and 95<sup>th</sup> percentiles compared to other elicited items, for all three  
568 scoring methods and ii) the differences in multi-modal values depending on scoring method (Fig. 3). Moreover,

569 differences between the alternative scoring methods are also greater, a fact that could be largely correlated to the  
570 less well-defined features of this eruption type compared to others (e.g. Plinian or sub-Plinian); the implications  
571 of this situation, discussed in section 5.1, should be therefore considered. It is important to highlight that, if we  
572 consider the sum of the mean probability of occurrences for any sub-Plinian and Plinian type eruption (rhyolitic  
573 or andesitic), we obtain a probability, for the next eruption NE, of 30-40%. A comparison of our results with  
574 those of Biass and Bonadonna (2013) is not straightforward, due to some differences in the eruption  
575 classification scheme. While these authors focus on eruptions with a specific VEI for their analyses, we have  
576 used the terminology sub-Plinian and Plinian, which spans between VEIs. Moreover, Biass and Bonadonna  
577 (2013) specifically calculated the probabilities of VEI 3, 4, 5 for the next eruption of  $VEI \geq 3$  in the next 100  
578 years, without considering the occurrence of multiple events of different type in the next 100 years.

579 Nevertheless, we have calculated, from the values in Table 3, the NE and N100 5<sup>th</sup>, 50<sup>th</sup>, 95<sup>th</sup> probability  
580 percentiles, and the mean probability of Plinian eruptions involving either rhyolitic or andesitic magmas (CM  
581 method only). These values are, respectively, [1.7, 8.7, 31] with mean value 12% for NE, and [2.9, 23, 65] with  
582 mean value 27% for N100, and they are both consistent with the sum of the probabilities of VEI 4 and 5  
583 eruptions (20.8%) calculated by Biass and Bonadonna (2013) for the next 100 years at Cotopaxi. Specifically, it  
584 seems evident that our estimations, which include uncertainty ranges, fully capture the probability calculated by  
585 using other datasets.

586 From the point of view of the parameters that are considered (Table 5), rhyolitic Plinian and sub-Plinian  
587 eruptions are expected to have longer median durations than their andesitic counterparts; this is consistent  
588 between CM, ERF and EW methods. Their uncertainty ranges are, however, slightly more skewed toward 95<sup>th</sup>  
589 percentile values than is the case in the andesitic scenarios. Andesitic eruptions with shorter durations are  
590 expected to have average plume height values that are slightly higher than those of rhyolitic eruptions, at least in  
591 terms of median values (for CM, ERF and EW). This implies, from a volcanic hazard point of view, a potentially  
592 longer duration of eruptive crises and potentially thicker deposits for rhyolitic eruptions than for andesitic ones.  
593 The judged longer duration of rhyolitic eruptions with respect to andesitic counterparts is partially confirmed by  
594 the eruptions considered in Table C1, since the mean of the durations for rhyolitic and andesitic eruptions are,  
595 respectively, 3300 and 790 min (both within our percentile ranges for both sub-Plinian and Plinian of Table 5).  
596 Concerning plume height, mean value from Table C1 are, for rhyolitic and andesitic eruptions, 18 and 19 km  
597 respectively. We recall, however, that plume height values from Table C1 are maximum plume heights, while  
598 our estimates are average plume heights.

599 The judged tephra fallout mass outputs for sub-Plinian and Plinian eruptions (both rhyolitic and  
600 andesitic) range from  $10^9$  to  $10^{12}$  kg, with medians of  $10^{10}$  kg for sub-Plinian and  $10^{11}$  kg for Plinian, comparable  
601 to estimations made for similar eruptions at Cotopaxi (Biass and Bonadonna 2011). For  
602 hydrovolcanic/continuous ash emission eruptions, the judged tephra fallout mass is lower relative to other  
603 eruption types (median values are all around  $10^8$  kg), but their duration could be fairly long (median > 1 month -  
604 see Table 5). Considering the highest conditional probability of these eruptions (both for the NE and the N100 ),  
605 long eruption durations have potentially severe consequences for aviation operations (Bernard et al. 2016) and  
606 for crop and greenhouses agriculture, the latter being one of Ecuador's most important sources of income (Knapp  
607 2017).

### 608 5.2.2 *Guagua Pichincha volcano*

609 The case of Guagua Pichincha is less complex than that of Cotopaxi since the composition of erupted  
610 magmas and the eruption types are more homogeneous. Nevertheless, the issue of the completeness of the  
611 stratigraphic record still remains. Considering the three eruption types on the event tree in Figure 2b, only  
612 Vulcanian to dome-forming eruptions (1999-2001 cycle) and Plinian eruptions (AD 1660) have been observed  
613 directly. Despite their apparent absence in the geologic record, in our logic tree we have inserted also sub-Plinian  
614 eruptions because they are sometimes difficult to distinguish from Plinian eruptions or from large Vulcanian  
615 events. No other eruptions with lower VEIs (including phreatic ones) are present in the geological record, a fact  
616 that seems to be partially confirmed by the (scarce) historical accounts of the "Historic" cycle (see Table 2).  
617 However, similarly to Cotopaxi, the possibility of unrecorded eruptions is not negligible, essentially because  
618 Guagua Pichincha is close to a region (to the west) characterized by a wet climate that does not favor  
619 preservation of thin volcanic deposits.

620 Consistent with these observations, the probability of "Other type" eruptions has a non-negligible  
621 median value of 7.5 - 11 % for the NE case (mean values of 13 - 18%) and 7.9 - 13 % for the N100 case (mean  
622 values of 13 - 22%), considering all three scoring methods. The eruption type for which the conditional  
623 probability for all the scoring methods and both for the NE and N100 cases is highest is the Vulcanian type  
624 (median values are 40 - 55 % and 56-66 % for NE and N100 respectively; mean values of 40 - 51% and 52 -  
625 60%), similar to the event that occurred during the 1999-2001 cycle. Again, in this case (as for the  
626 "hydrovolcanic/continuous ash emission" case of Cotopaxi, see previous section) greater uncertainties and

627 differences in multimodal values (Fig. 4) arising from the scoring methods are limited and reasonably correlated  
628 with the less well-defined features of this eruption type compared to others (e.g. Plinian or sub-Plinian).

629 In this case study, the situation is similar to that of the hydrovolcanic/continuous ash emission eruption  
630 for Cotopaxi volcano (see section 5.2.1), where the probability density function of the CM scoring method  
631 differs from those of the ERF and EW methods (Table 4 and Fig. 4). We also remark that the summed mean  
632 conditional probabilities for Plinian and sub-Plinian eruptions are 26 – 43 % (NE case) and 50 – 58 % (N100  
633 case). Pyroclastic density currents are likely to be one of the worst hazards of a Plinian or sub-Plinian eruption at  
634 Guagua Pichincha. However, due to topographic constraints, these currents are likely to be confined mainly to  
635 the poorly inhabited valleys to the NW and SW of the active crater (Robin et al. 2008). On the other hand, tephra  
636 fallout will represent a major hazard for the city of Quito, since there are historical accounts of ash fall during the  
637 AD 1660 eruption (Robin et al. 2008) but also during the much smaller AD 1999 Vulcanian eruption (Naumova  
638 et al. 2007; Volentik and Houghton 2015).

639 Finally, we underline that: i) ESPs from Table 6 are consistent both with other estimations for Guagua  
640 Pichincha volcanoes (e.g. total mass estimated by Barberi et al. 1992 for Layers 3/5) and values reported in  
641 Table C1; ii) there is a similarity between the elicited uncertainty distributions of ESPs for Plinian and sub-  
642 Plinian eruptions of Guagua Pichincha with those for the same-size eruption types with andesitic magmas at  
643 Cotopaxi volcano (Tables 5 and 6). This similarity represents consistent reasoning by our experts, since the  
644 magma compositions of Guagua Pichincha products are dacitic to andesitic (Robin et al. 2010).

## 645 6. Conclusions

646 This paper addresses the probabilities of different explosive eruption types and their main ESPs at  
647 Cotopaxi and Guagua Pichincha volcanoes. We analyzed these probabilities from both “next eruption” and “next  
648 100 years” perspectives, through the employment of well-established structured expert judgment analysis  
649 procedures involving twenty experts with different backgrounds, professional interests and volcanological  
650 experiences. Results are presented, for each eruption parameter, as uncertainty distributions based on probability  
651 functions defined by three percentiles (5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup>). By employing different scoring methods with different  
652 features and advantages (the Classical Model, the Expected Relative Frequency method, and the Equal Weights  
653 pooling rule), the user of these elicitation data is given the opportunity to use the results from one single  
654 approach or to choose some combination of the results.

655 In addition, Principal Component Analysis was used for sensitivity testing the outcomes from different  
656 sub-groups of experts, the latter subdivided in terms of experience (A1/A2 – Experienced researchers/Early-  
657 career researchers), background (B1/B2 – Geologists/Mathematicians-Modelers) and institution affiliation at the  
658 time of the elicitation (C1/C2 – Clermont-Ferrand/Quito). Analysing results from the Classical Model highlights  
659 that the outcomes considering all the experts are equally distant from those of sub-groups C1/C2, while they are  
660 closer to those of sub-groups A1 and B1 respectively. In other words, institutional affiliation was not a  
661 determinant of overall decision maker (DM) findings, whereas they were somewhat influenced by experienced  
662 researchers and by those with geological backgrounds.

663 Further studies should address two aspects: i) the incompleteness of the geologic record for both  
664 Cotopaxi and Guagua Pichincha volcanoes; ii) the causes of major sources of uncertainty highlighted by our  
665 expert judgment results. With respect to this latter point, an extended discussion of the rationale behind the ESPs  
666 estimates and probability forecasts could enhance their scientific impact. This includes the probability of  
667 occurrence and the ESPs of small size eruptions (hydrovolcanic/long-lasting ash emission for Cotopaxi,  
668 Vulcanian for Guagua Pichincha), the probability of occurrence and the ESPs of the rhyolitic eruptions of  
669 Cotopaxi, and the detailing of the ‘other type’ eruptions.

670 Nevertheless, the probability distributions were found to be robust with respect to different density  
671 estimation methods and expert aggregation models. Thus, the reported judgments picture the knowledge of the  
672 elicited group of experts, and they could only be modulated by any substantial new data set, information or  
673 interpretation of the volcanic record of Cotopaxi and Guagua Pichincha volcanoes. Notwithstanding the  
674 limitations of the analysis described above, our estimates represent crucial input information for the development  
675 of quantitative hazard and risk maps of eruptive phenomena in the region, especially for what concerns the  
676 uncertainty quantification. We remark, moreover, that our approach is not inconsistent with previous studies that  
677 involved an analysis of the past eruptive record (Biass and Bonadonna 2013). Nevertheless, we present some  
678 information that was rather difficult to obtain without using expert judgment techniques. In particular, we  
679 performed uncertainty quantification on the probability estimates provided and on the evaluation of the case of  
680 more than one type of eruption occurring in the next 100 years.

681  
682 With respect to hazard implications for each volcano, the main results are:

- 683 • for Cotopaxi, the most probable next eruption is considered to be a hydrovolcanic/long-lasting  
684 ash emission involving andesitic magma, similar to that of AD 2015. However, the chance of a

685 rhyolitic event is not negligible although very uncertain, with a median probability of 8-12%  
686 (mean values 13-20%). The median probability that there will be at least one eruption of this  
687 type within the next 100 years is 43 - 55% (mean values in 43 - 51%). Despite these eruptions  
688 have relatively low magnitude/intensity, their long durations (median of ~1 month) can have a  
689 significant negative impact on aviation safety and both crop and greenhouse cultivations. For  
690 larger magnitude eruptions (i.e. sub-Plinian and Plinian), rhyolitic ones have lower  
691 probabilities of occurrences than andesitic ones, but they could pose a higher threat due to their  
692 potential longer durations and larger eruption masses than their andesitic counterparts. As a  
693 whole, summing the mean probabilities that the next eruption will be either sub-Plinian or  
694 Plinian (whether rhyolitic or andesitic) returns a substantial, significant mean probability of 30  
695 - 40%;

- 696 • for Guagua Pichincha, the most probable next eruption is a vulcanian event (similar to that of  
697 AD 1999), with a median probability of occurrence of 40 – 55 % (mean values of 40 - 51%).  
698 The median probability that within the next 100 years there will be at least one eruption of this  
699 type is greater: 55 - 66 % (mean values of 52 - 60%). The larger magnitude eruption types  
700 (sub-Plinian or Plinian) have, in turn, a summed mean probability of occurrence for the next  
701 eruption of 26 – 43 %, while for the next 100 years the same combined mean probability is of  
702 50 – 58 %.

703 In summary, while small or moderate magnitude eruptions are considered most likely candidates for the  
704 next eruption at Cotopaxi and at Guagua Pichincha, the elicited event probabilities for violent explosive  
705 eruptions represent a plausible prospect at either volcano in the long or short term. Indeed, the possibility exists,  
706 at a non-trivial probability, that the next eruption in either case could be on the scale of a sub-Plinian or Plinian  
707 eruption.

## 708 **Appendix A: Performance-based Expert Judgment**

709 In general, with the performance-based elicitation procedure underpinning the Classical Model  
710 approach (Cooke 1991; Aspinall 2006), statistical accuracy (e.g. calibration) and informativeness scores are  
711 derived for each expert from a set of ‘seed questions’. These items comprise factual questions, the true  
712 quantitative values of which an expert is not expected to know precisely but, in respect of which, he/she is  
713 expected to provide meaningful credible intervals that capture those values reliably and informatively, by  
714 informed reasoning.

715 Concerning the two scores, statistical accuracy (“calibration”) represents the p-value that the expert’s  
716 inter-quantile probabilities, summed over several items, match the underlying probability vector sample  
717 distribution implied by the 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> percentiles, as assessed by the expert per item. If the actual  
718 realization values are indeed drawn independently from such a distribution, with quantiles as stated by the  
719 expert, then deviations in the expert’s assessments are asymptotically distributed as a chi-square variable with 3  
720 degrees of freedom. The corresponding p-value for goodness-of-fit yields a measure of the expert’s statistical  
721 accuracy (or calibration). At the same time, the expert’s informativeness score is the degree to which their  
722 uncertainty distributions are concentrated; that is, the smaller the distance between the 5<sup>th</sup> and the 95<sup>th</sup>  
723 percentiles, the more an expert is informative.

724 In general, it can be shown that these two performance-based scores in the Classical Model refer to  
725 “orthogonal” properties of the expert’s judgment capability: i.e. their statistical accuracy versus informativeness.  
726 The challenge for the expert, therefore, is to optimize their overall performance score – which is the product of  
727 these two metrics - by maximizing them jointly. This is a tricky judgmental balancing act: the expert’s  
728 performance score will be penalized if they over-accentuate one at the expense of the other by being more  
729 precise or more informative in their judgments on a question than their understanding of the uncertainty  
730 warrants.

731 With respect to the scoring methods mentioned in Section 3.1, the two performance-based methods CM  
732 (the Classical Model: Cooke 1991) and ERF (Expected Relative Frequency method; Flandoli et al. 2011)  
733 significantly differ in their scoring metrics: CM evaluates the statistical distribution of the known values with  
734 respect to the expert’s percentiles, and, on a second order, the diameter of the corresponding uncertainty range;  
735 ERF measures the likelihood of “accurate” judgments, i.e. those relatively close to the true value of a question.

736 Variances of the performance scores, which indicate how they differ, tend to be highest with the CM  
737 approach, lower with ERF (and trivially null with the Equal Weights EW rule, which has no performance  
738 measure). We remark that for the purpose of defining the global decision makers (DMs) we always performed a  
739 weighted combination (probability mixture) of maximum entropy distributions. That is, we did not use triangular  
740 functions and quantile pooling when defining the DMs (Bevilacqua, 2016). This differs from the traditional  
741 approach followed in the ERF method but simplifies the comparison of the results by focusing only on the  
742 differences in the scores. We remark that the calculation of the ERF scores is still based on triangular functions.

743 According to Flandoli et al. (2011), the main outcomes for each scoring methods are:

- 744 • The main advantage of using the CM method is that it is possible to highlight those experts with the  
745 best combination of calibration and informativeness scores (these are not measures of each expert's  
746 knowledge about the problem but indicate, objectively, their capability to express informative  
747 uncertainties about a range of subject matter items). In particular, when group's judgments are pooled,  
748 this latter aspect generally produces smaller (and thus more informative) uncertainty bounds between  
749 the 5<sup>th</sup> and 95<sup>th</sup> percentiles for each question. Moreover, Flandoli et al. (2011) demonstrate that the  
750 uncertainty range described by the CM is usually the best estimate of the supposed 'true' uncertainty;
- 751 • In contrast, the EW method describes the maximum uncertainty bounds (pointing toward a more  
752 "conservative" approach) but it does not take into account the information about individual expert's  
753 calibration (i.e. statistical accuracy) obtained from the seed questionnaire;
- 754 • Finally, the ERF method has been shown by Flandoli et al. (2011) to conceptually provide the most  
755 accurate estimates of supposed 'true' central values (i.e. the median values of the distributions).

756 For this study, during the first plenary session, the experts benefited from a detailed presentation of the  
757 eruptive history of the two volcanoes considered. Moreover, details about expert judgment techniques have been  
758 provided, which has been followed by final discussion on the topics presented. During the first part of the  
759 session, the experts were invited to provide their judgments on 16 seed questions. However, two questions had  
760 ambiguous formulations, which led to multiple interpretations by the experts. These questions were excluded  
761 from the performance scoring analysis for this reason. During the first stage, the experts were also asked to  
762 answer two different target questionnaires, respectively for Cotopaxi and Guagua Pichincha, whereby the experts  
763 were asked to evaluate the relative conditional probabilities of different eruptive styles/magma compositions  
764 over a single specific future timeframe (i.e. the next 100 years). After a first pass through the questions and  
765 following discussions with the experts, some issues were identified within the group's responses about several  
766 target items for both Cotopaxi and Guagua Pichincha. More specifically, some ambiguities were identified:

- 767 • for the meaning of the term "Magmatic Unrest"
- 768 • for the definition of an "Eruption"
- 769 • in the distinction between "Rhyolitic" and "Andesitic" magmas for Cotopaxi volcano
- 770 • in relation to questions about the future behavior of the volcano, queries were raised about whether the  
771 experts were considering "the next eruption" or an eruption in "the next 100 years", despite having separated the  
772 two frameworks of NE and N100.

773 In particular, it has been clarified to the participants that in this study the term "eruption" means a period of  
774 continuous volcanic activity, where the products erupted have almost the same composition and the geophysical  
775 signals are continuous, although fluctuant. In this sense, an eruption is separated from another eruption by a  
776 sufficiently long quiescence time (several months to years), where no volcanic activity is observed.

777 Because of these concerns (such issues usually arise with any expert elicitation), some question wordings were  
778 changed and other questions added to the set identifying which of the two alternative timeframes should be  
779 considered. The experts were then given the opportunity to revise their responses via email after some  
780 clarification notes and additional information were circulated to the participants. It is important to underline that  
781 experts have not been asked to provide an explanation to their answers.

## 782 **Appendix B: calculated mean values from probability distributions**

783 In this appendix we report the calculated means for the probability distributions from Tables 3-6. Such  
784 values have been calculated for both Cotopaxi (Table B1) and Guagua Pichincha (Table B2). It is worth  
785 mentioning that the sum of the mean probabilities of mutually exclusive scenarios sum to 100% in the NE case.  
786 In contrast, the sum is greater than 100% in the N100 case, because the possible occurrence of more than one  
787 type of eruption in the next 100 years was not excluded.

788

## 789 **Appendix C: comparison of some ESPs with global data**

790 Table C1 gives the data of the duration of well-studied eruptions involving, respectively, andesitic,  
791 dacitic, and rhyolitic magmas. To improve consistency of our approach with the reported data, the definition of  
792 eruption used for calculating durations is different with respect to the one reported in Appendix A, and it reflects  
793 the definition of eruption duration proposed by Mastin et al. (2009), which is to be the time period over which a  
794 significant amount of ash is continuously emitted into the atmosphere. Plume heights are maximum estimations.

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## FIGURE CAPTIONS

**Figure 1.** a) Location of Cotopaxi and Guagua Pichincha volcanoes. b) and c) are enlargements of a). Coordinates expressed in the UTM WGS84 17S coordinate system. Service Layer Credits, source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN and the GIS User Community.

**Figure 2.** Logic trees for a) Cotopaxi and b) Guagua Pichincha volcanoes. Each of the lowest branch of the logic trees represents a possible eruptive scenario with the maximum expected eruptive style.

**Figure 3.** Cotopaxi volcano. Probability density functions of conditional probabilities for a) the next eruption and b) the next 100 years. For each graph, it is reported on the x-axis the Decision Maker's response (in %), and on the y-axis the distributions of, respectively, the Classical Model (red), the Expected Relative Frequency (blue) and the Equal Weight (green) Decision Makers.

**Figure 4.** Guagua Pichincha volcano. Probability density functions of conditional probabilities for a) the next eruption and b) the next 100 years. For each graph, it is reported on the x-axis the Decision Maker's response (in %), and the distributions of, respectively, the Classical Model (red), the Expected Relative Frequency (blue) and the Equal Weight (green) Decision Makers.

**Figure 5.** Eigenvectors of the different sub-groups (A1 – Senior researchers; A2 – Early-career researchers; B1 – Geologists; B2 – Mathematicians/Modelers; C1 – Clermont-Ferrand; C2 – Quito) plotted against the eigenvector of the whole group of experts (All). All the eigenvectors have been derived from the solutions of the Classical Model (CM) listed in Tables 3-6. Dim1 and Dim2 are the percentages of the x and y component of each eigenvector.

## TABLE CAPTIONS

**Table 1.** Selected eruptions from Cotopaxi volcano used to define the typologies of eruption that compose logic trees of Figure 2. References: <sup>1</sup>Hall and Mothes (2008); <sup>2</sup>Pistolesi et al. (2011); <sup>3</sup>Tsunematsu and Bonadonna (2015); <sup>4</sup>Bernard et al. (2016).

**Table 2.** Selected eruptions from Guagua Pichincha volcano used to define the typologies of eruption that compose logic trees of Figure 2. References: <sup>1</sup>Barberi et al. (1992); <sup>2</sup>Robin et al. (2008); <sup>3</sup>Robin et al. (2010).

**Table 3.** Conditional probabilities of different eruption types for the “next eruption” (NE) and “next 100 years” (N100) cases at Cotopaxi.

**Table 4.** Conditional probabilities of different eruption types for the “next eruption” (NE) and “next 100 years” (N100) cases at Guagua Pichincha.

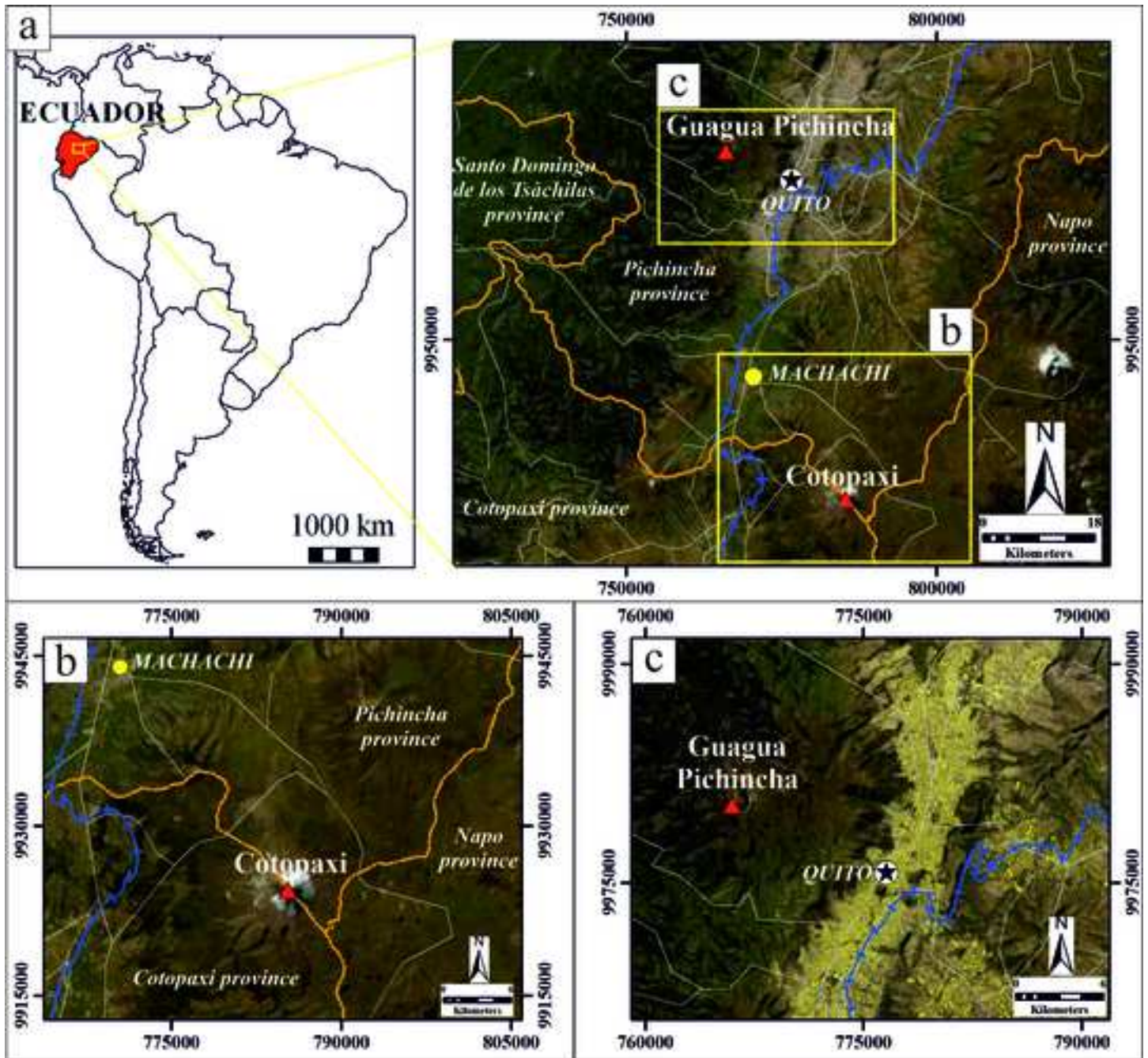
**Table 5.** Uncertainty ranges for eruptive source parameters of Cotopaxi volcano. For durations, 1 day = 1440 min., 1 week = 10080 min., 1 month = 43200 min., 1 year = 525600 min.

**Table 6.** Uncertainty ranges for eruptive source parameters of Guagua Pichincha volcano. For durations, 1 day = 1440 min., 1 week = 10080 min., 1 month = 43200 min., 1 year = 525600 min.

**Table B1.** Mean values for the probability of occurrences (next eruption NE and next 100 years N100) for the classical model (CM), expected relative frequency (ERF) and equal weight (EW) rule for Cotopaxi and Guagua Pichincha volcanoes.

**Table B2.** Mean values for the eruptive source parameters (duration, total mass of the tephra fallout deposit and average plume height) for the classical model (CM), expected relative frequency (ERF) and equal weight (EW) rule for Cotopaxi and Guagua Pichincha volcanoes.

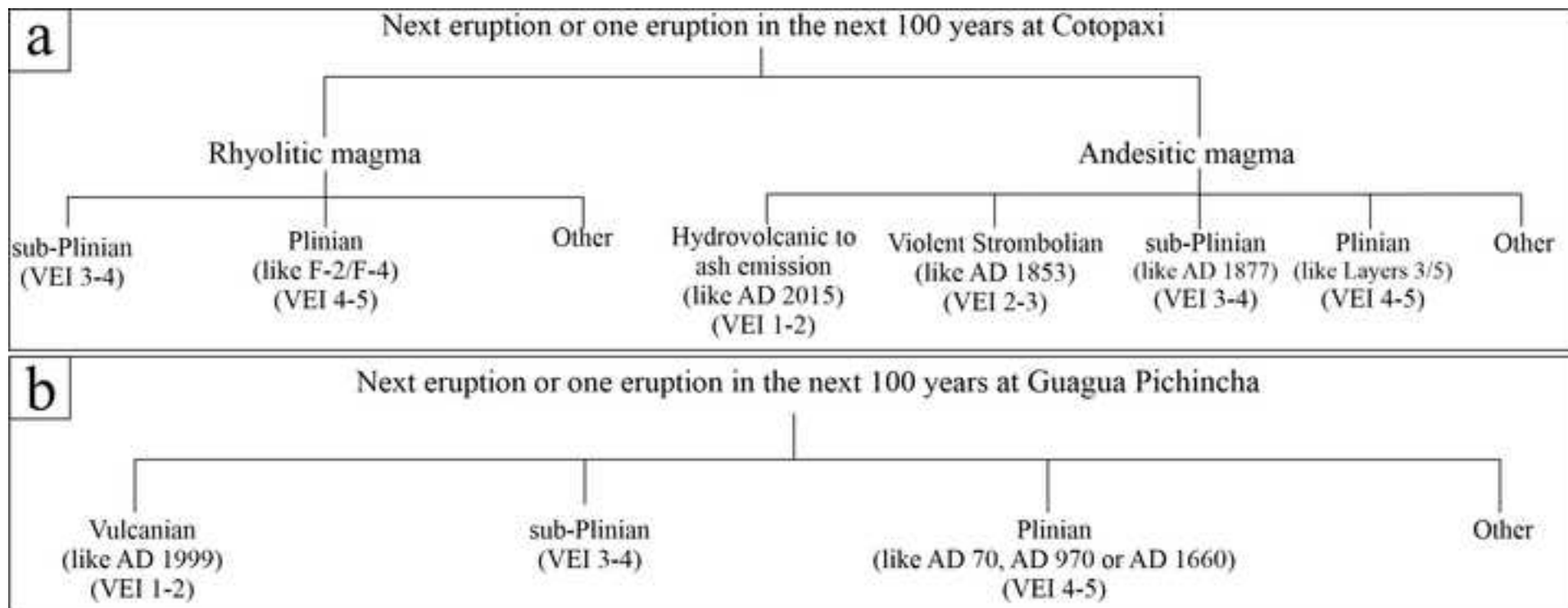
**Table C1.** Selected eruptions involving andesitic, dacitic and rhyolitic magmas. References: <sup>1</sup>Gouhier et al. (2019); <sup>2</sup>Mastin et al. (2009); <sup>3</sup>Risacher and Alonso (2001); <sup>4</sup>Carey et al. (2010); <sup>5</sup>Bonadonna et al. (2015); <sup>6</sup>Durant et al. (2012).

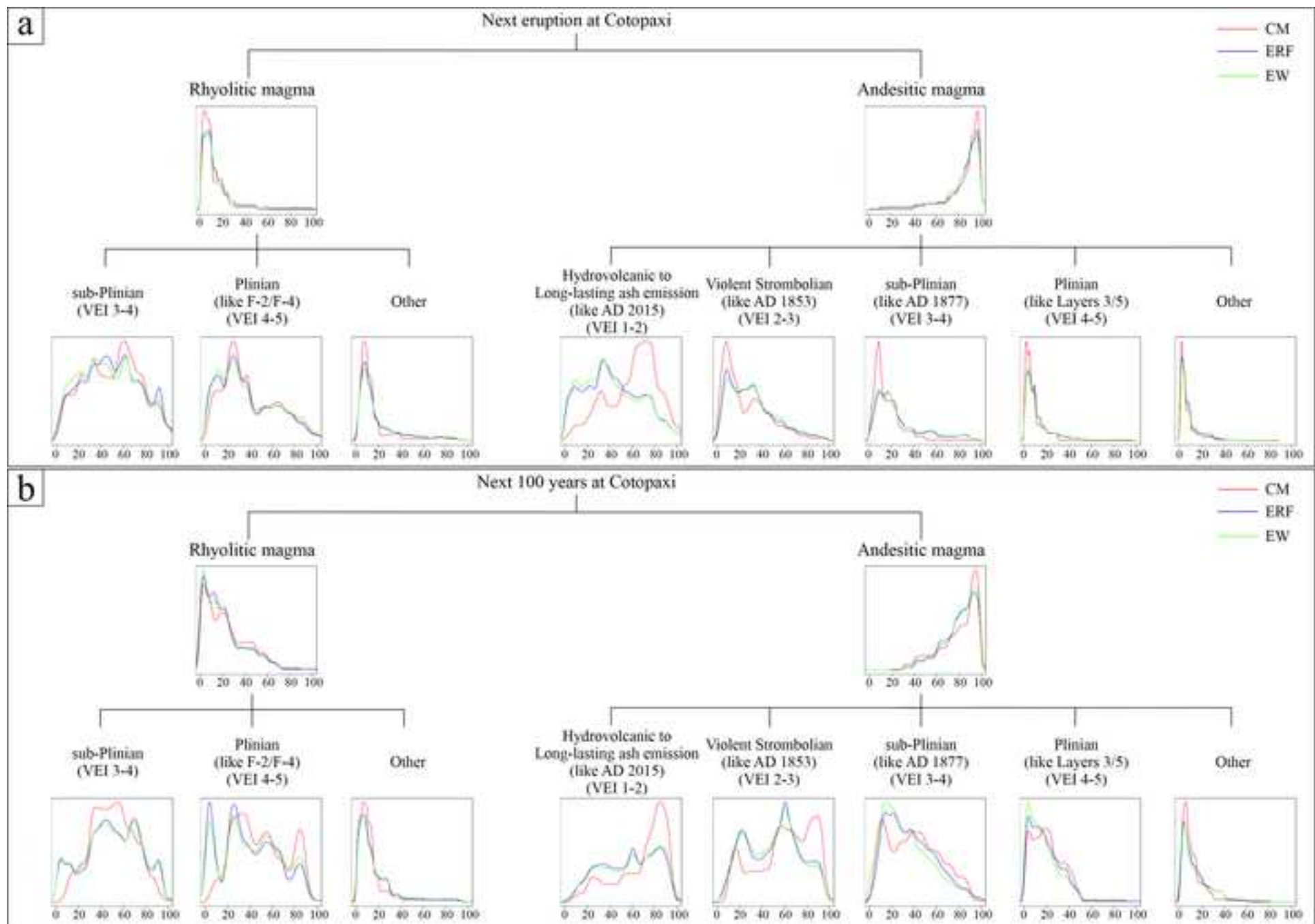


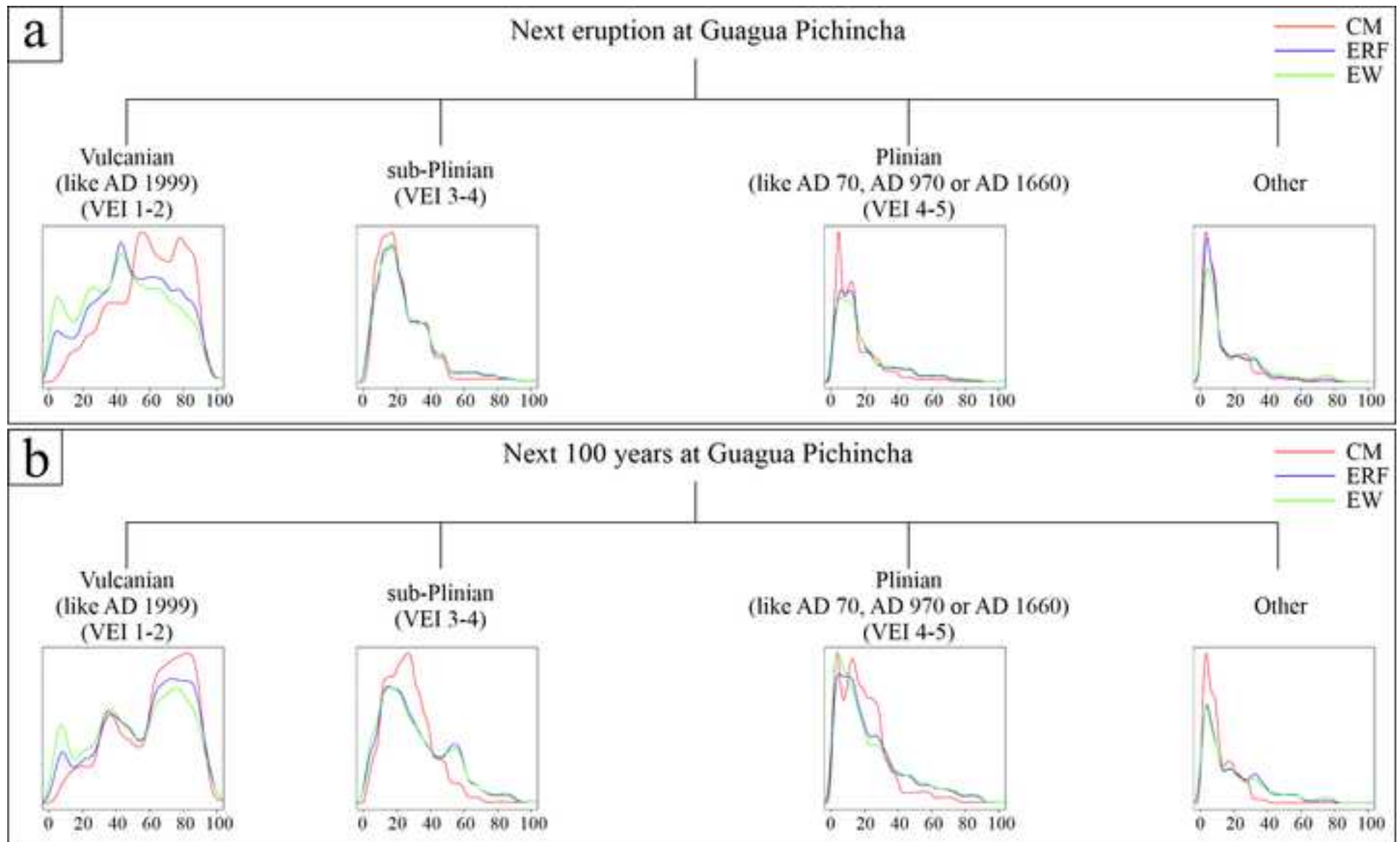
**Legend**

- Province boundary
- Town Building
- ▲ Volcano
- Railroad
- Major road











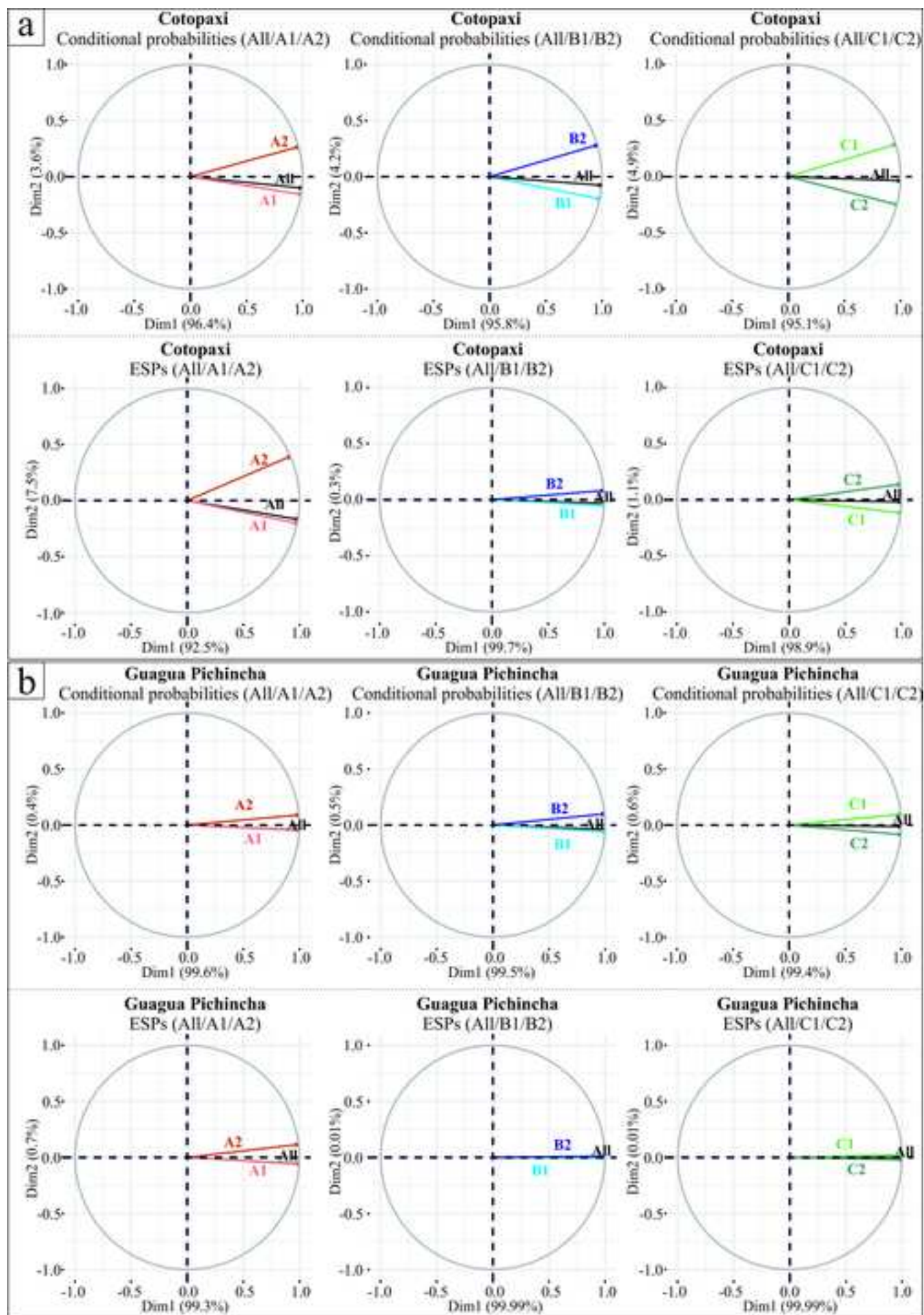


Table 1

<b>Eruptive Cycle or Eruption Name</b>	<b>N° eruptions</b>	<b>DRE volume (km<sup>3</sup>)</b>	<b>Age/Date</b>	<b>Maximum VEI</b>	<b>Eruptive style(s)</b>	<b>Magma composition</b>	<b>Ref(s)</b>
2015	1	0.0001	AD 2015	1-2	Hydrovolcanic to continuous ash emission	Andesitic	1,2,3,4
1877	1	0.02-0.06	AD 1877	4	SubPlinian		
1853	1	0.02-0.12	AD 1853	2-3	Violent Strombolian		
X/Layer 3	1	2.4	~0.9 ka	4-5	Plinian		
Y/Layer 5	1	0.5	~1.1 ka	4	Plinian		
F-4	>1	1.59-8.3	~5.8 ka	5	Plinian	Rhyolitic	1
F-2	>1	2.37-8.6	~7.8 ka	?	Plinian		

Table 2

<b>Eruptive Cycle Name</b>	<b>N° eruptions</b>	<b>DRE volume (km3)</b>	<b>Age</b>	<b>Maximum VEI of cycle</b>	<b>Eruptive style(s)</b>	<b>Refs</b>
1999-2001	~13	?	AD 1999-2001	0 to 1-2	~5 Vulcanian 8 Dome forming	1,2,3
Historic	4	>0.2 (of the largest eruption)	AD 1660 (of the largest eruption)	3-4	Plinian (of the largest eruption)	
X century	>1	>>0.6 (of the largest eruption)	AD 970 (of the largest eruption)	5	Plinian (of the largest eruption)	
I century	1	>0.5	AD 70	4	Plinian	

Table 3

Variable	% - 5 <sup>th</sup> /Median/95 <sup>th</sup>								
	CM			ERF			EW		
<i>% sub-Plinian Rhyolitic (NE)</i>	< 0.1	<b>3.7</b>	19	< 0.1	<b>4.6</b>	26	< 0.1	<b>4.7</b>	29
<i>% Plinian Rhyolitic (NE)</i>	< 0.1	<b>2.7</b>	15	< 0.1	<b>3.1</b>	20	< 0.1	<b>3.4</b>	24
<i>% Other type Rhyolitic (NE)</i>	< 0.1	<b>0.9</b>	7.5	< 0.1	<b>1.4</b>	12	< 0.1	<b>1.6</b>	14
<i>% Hydr./Ash em. Andesitic (NE)</i>	13	<b>44</b>	71	1.8	<b>28</b>	57	1.9	<b>26</b>	56
<i>% Violent Stromb. Andesitic (NE)</i>	1.3	<b>15</b>	43	1.9	<b>18</b>	47	2.0	<b>19</b>	48
<i>% sub-Plinian Andesitic (NE)</i>	0.4	<b>9.5</b>	33	1.2	<b>15</b>	45	1.1	<b>14</b>	44
<i>% Plinian Andesitic (NE)</i>	< 0.1	<b>4.2</b>	23	0.1	<b>5.9</b>	31	< 0.1	<b>5.5</b>	31
<i>% Other type Andesitic (NE)</i>	< 0.1	<b>3.5</b>	25	< 0.1	<b>4.0</b>	26	< 0.1	<b>4.0</b>	27
<i>% sub-Plinian Rhyolitic (N100)</i>	< 0.1	<b>7.3</b>	40	< 0.1	<b>6.5</b>	41	< 0.1	<b>6.0</b>	41
<i>% Plinian Rhyolitic (N100)</i>	< 0.1	<b>6.7</b>	41	< 0.1	<b>4.3</b>	36	< 0.1	<b>4.6</b>	37
<i>% Other type Rhyolitic (N100)</i>	< 0.1	<b>1.5</b>	18	< 0.1	<b>1.4</b>	18	< 0.1	<b>1.5</b>	20
<i>% Hydr./Ash em. Andesitic (N100)</i>	< 0.1	<b>55</b>	87	< 0.1	<b>43</b>	84	< 0.1	<b>45</b>	85
<i>% Violent Stromb. Andesitic (N100)</i>	< 0.1	<b>47</b>	87	< 0.1	<b>38</b>	81	< 0.1	<b>38</b>	81
<i>% sub-Plinian Andesitic (N100)</i>	< 0.1	<b>28</b>	75	< 0.1	<b>25</b>	72	< 0.1	<b>22</b>	73
<i>% Plinian Andesitic (N100)</i>	< 0.1	<b>14</b>	43	< 0.1	<b>12</b>	48	< 0.1	<b>11</b>	51
<i>% Other type Andesitic (N100)</i>	< 0.1	<b>6.1</b>	41	< 0.1	<b>7.4</b>	47	< 0.1	<b>7.1</b>	50

Table 4

Variable	% - 5 <sup>th</sup> /Median/95 <sup>th</sup>								
	CM			ERF			EW		
<i>% Vulcanian (NE)</i>	4.7	<b>55</b>	81	0.5	<b>45</b>	77	0.3	<b>40</b>	76
<i>% sub-Plinian (NE)</i>	1.8	<b>18</b>	55	1.0	<b>20</b>	60	0.3	<b>19</b>	60
<i>% Plinian (NE)</i>	0.3	<b>9.9</b>	46	0.4	<b>13</b>	54	0.4	<b>14</b>	57
<i>% Other type (NE)</i>	< 0.1	<b>7.5</b>	43	< 0.1	<b>8.8</b>	48	< 0.1	<b>11</b>	54
<i>% Vulcanian (N100)</i>	5.5	<b>66</b>	94	1.6	<b>62</b>	96	1.2	<b>56</b>	96
<i>% sub-Plinian (N100)</i>	2.1	<b>25</b>	63	0.9	<b>26</b>	83	< 0.1	<b>26</b>	81
<i>% Plinian (N100)</i>	1.0	<b>17</b>	66	< 0.1	<b>17</b>	82	< 0.1	<b>16</b>	80
<i>% Other type (N100)</i>	< 0.1	<b>7.9</b>	37	0.1	<b>13</b>	70	< 0.1	<b>13</b>	75

Table 5

Variable	5 <sup>th</sup> /Median/95 <sup>th</sup>								
	CM			ERF			EW		
<i>Mean duration sub-Plinian Rhyolitic (minutes)</i>	15	<b>170</b>	6300	13	<b>210</b>	4000	10	<b>210</b>	4100
<i>Total mass tephra sub-Plinian Rhyolitic (10<sup>9</sup> kg)</i>	2.4	<b>53</b>	760	0.2	<b>39</b>	740	0.2	<b>36</b>	740
<i>Average plume height sub-Plinian Rhyolitic (km)</i>	5.6	<b>16</b>	25	2.7	<b>17</b>	28	2.1	<b>17</b>	28
<i>Mean duration Plinian Rhyolitic (minutes)</i>	27	<b>340</b>	13000	19	<b>400</b>	8900	15	<b>330</b>	8800
<i>Total mass tephra Plinian Rhyolitic (10<sup>9</sup> kg)</i>	8.8	<b>410</b>	7600	0.005	<b>450</b>	14000	0.002	<b>450</b>	35000
<i>Average plume height Plinian Rhyolitic (km)</i>	10	<b>24</b>	40	7.8	<b>26</b>	40	6.5	<b>26</b>	40
<i>Mean duration Hyd./Ash em. Andesitic (minutes)</i>	220	<b>41000</b>	1200000	52	<b>48000</b>	800000	35	<b>44000</b>	710000
<i>Total mass tephra Hyd./Ash em. Andesitic (10<sup>9</sup> kg)</i>	0.0001	<b>0.8</b>	110	0.0002	<b>0.8</b>	60	0.0001	<b>0.6</b>	58
<i>Average plume height Hyd./Ash em. Andesitic (km)</i>	0.3	<b>3.8</b>	14	0.2	<b>3.2</b>	13	0.2	<b>3.1</b>	13
<i>Mean duration Violent Str. Andesitic (minutes)</i>	6	<b>42</b>	6000	6	<b>41</b>	12000	6	<b>46</b>	32000
<i>Total mass tephra Violent Str. Andesitic (10<sup>9</sup> kg)</i>	0.01	<b>6.0</b>	92	0.004	<b>1.5</b>	74	0.004	<b>0.8</b>	71
<i>Average plume height Violent Str. Andesitic (km)</i>	1.5	<b>8.3</b>	18	1.5	<b>9.9</b>	26	1.4	<b>9.6</b>	27
<i>Mean duration sub-Plinian Andesitic (minutes)</i>	9	<b>75</b>	9400	9	<b>79</b>	5500	8	<b>73</b>	6000
<i>Total mass tephra sub-Plinian Andesitic (10<sup>9</sup> kg)</i>	1.2	<b>34</b>	430	0.05	<b>21</b>	270	0.04	<b>18</b>	290
<i>Average plume height sub-Plinian Andesitic (km)</i>	6.6	<b>18</b>	25	7.9	<b>19</b>	28	7.4	<b>19</b>	28
<i>Mean duration Plinian Andesitic (minutes)</i>	11	<b>180</b>	19000	12	<b>200</b>	11000	12	<b>180</b>	12000
<i>Total mass tephra Plinian Andesitic (10<sup>9</sup> kg)</i>	11	<b>220</b>	4200	0.07	<b>320</b>	9900	0.04	<b>270</b>	14000
<i>Average plume height Plinian Andesitic (km)</i>	13	<b>25</b>	35	14	<b>26</b>	35	13	<b>26</b>	36

Table 6

Variable	5 <sup>th</sup> /Median/95 <sup>th</sup>								
	CM			ERF			EW		
<i>Mean duration Vulcanian (minutes)</i>	0.9	<b>14</b>	2300	1	<b>17</b>	8800	1	<b>19</b>	2E+05
<i>Total mass tephra Vulcanian ( 10<sup>9</sup> kg)</i>	2E-04	<b>1.6</b>	71	2E-04	<b>0.4</b>	51	1E-04	<b>0.3</b>	55
<i>Average plume height Vulcanian (km)</i>	1.0	<b>8</b>	19	1.1	<b>9.3</b>	21	0.6	<b>8.9</b>	21
<i>Mean duration sub-Plinian (minutes)</i>	9	<b>88</b>	6400	8	<b>100</b>	4300	6	<b>96</b>	4300
<i>Total mass tephra sub-Plinian ( 10<sup>9</sup> kg)</i>	0.4	<b>28</b>	660	0.03	<b>18</b>	470	0.02	<b>13</b>	460
<i>Average plume height sub-Plinian (km)</i>	6.9	<b>17</b>	25	7.9	<b>18</b>	27	7.4	<b>18</b>	28
<i>Mean duration Plinian (minutes)</i>	11	<b>190</b>	13000	11	<b>240</b>	9200	9	<b>210</b>	9100
<i>Total mass tephra Plinian ( 10<sup>9</sup> kg)</i>	1.6	<b>170</b>	3600	0.03	<b>170</b>	4400	0.03	<b>140</b>	6800
<i>Average plume height Plinian (km)</i>	13	<b>24</b>	34	14	<b>26</b>	34	13	<b>25</b>	34

<b>Eruption Cotopaxi</b>	<b>Mean values</b>					
	<b>NE (%): SUM=100</b>			<b>N100 (%)</b>		
	<b>CM</b>	<b>ERF</b>	<b>EW</b>	<b>CM</b>	<b>ERF</b>	<b>EW</b>
<i>sub-Plinian Rhyolitic</i>	5.9	7.7	8.1	12	11	11
<i>Plinian Rhyolitic</i>	4.6	5.6	6.4	12	9.2	9.7
<i>Other type Rhyolitic</i>	2.0	3	3.6	4.2	4.3	4.7
<i>Hydr./Ash em. Andesitic</i>	44	28	27	51	43	44
<i>Violent Stromb. Andesitic</i>	18	21	21	45	38	38
<i>sub-Plinian Andesitic</i>	12	18	17	31	29	27
<i>Plinian Andesitic</i>	6.9	9.4	9.1	17	17	16
<i>Other type Andesitic</i>	6.8	7.2	7.5	11	13	14
<b>Eruption Guagua Pichincha</b>	<b>Mean values</b>					
	<b>NE (%): SUM=100</b>			<b>N100 (%)</b>		
	<b>CM</b>	<b>ERF</b>	<b>EW</b>	<b>CM</b>	<b>ERF</b>	<b>EW</b>
<i>Vulcanian</i>	51	44	40	60	56	52
<i>sub-Plinian</i>	22	24	24	28	32	32
<i>Plinian</i>	14	18	19	21	25	24
<i>Other type</i>	13	15	18	13	21	22



Table B2

<b>Eruption Cotopaxi</b>	<b>Mean values</b>								
	<b>Duration (min)</b>			<b>Total mass fallout (10<sup>9</sup> kg)</b>			<b>Average plume height (km)</b>		
	<b>CM</b>	<b>ERF</b>	<b>EW</b>	<b>CM</b>	<b>ERF</b>	<b>EW</b>	<b>CM</b>	<b>ERF</b>	<b>EW</b>
<i>sub-Plinian Rhyolitic</i>	200	190	180	49	30	27	14	15	14
<i>Plinian Rhyolitic</i>	370	340	290	270	150	120	22	23	22
<i>Hydr./Ash em. Andesitic</i>	29000	24000	19000	0.5	0.4	0.2	3.2	2.7	2.6
<i>Violent Stromb. Andesitic</i>	73	88	120	4.0	1.1	0.9	7.3	8.3	8.1
<i>sub-Plinian Andesitic</i>	110	96	97	27	11	9.3	16	18	17
<i>Plinian Andesitic</i>	230	210	190	240	180	140	24	25	25
<b>Eruption Guagua Pichincha</b>	<b>Mean values</b>								
	<b>Duration (min)</b>			<b>Total mass fallout (10<sup>9</sup> kg)</b>			<b>Average plume height (km)</b>		
	<b>CM</b>	<b>ERF</b>	<b>EW</b>	<b>CM</b>	<b>ERF</b>	<b>EW</b>	<b>CM</b>	<b>ERF</b>	<b>EW</b>
<i>Vulcanian</i>	25	30	41	0.4	0.2	0.2	6.6	7.2	6.3
<i>sub-Plinian</i>	130	110	110	24	10	7.8	16	17	17
<i>Plinian</i>	240	230	200	130	98	73	24	24	24

Table C1

Eruption	Magma type	VEI	Eruptive style	Duration (min)	Mass of fallout deposit (10 <sup>9</sup> kg)	Plume height (km)	Ref(s)
Redoubt (USA), 2009	Andesitic	-	Vulcanian	87	14	15	1
Soufrière Hills (Monsterrat, UK), 1997	Andesitic	-	Vulcanian	60	0.5	11	1
Lascar (Chile), 1993	Andesitic	-	sub-Plinian	2883	350	21	1,3
Ruapehu (New Zealand), June 1996	Andesitic	3	sub-Plinian	600	4.2	8.5	1,2
Nevado del Ruiz (Colombia), 1985	Andesitic	3	-	18	-	26	2
Spurr (USA), June 1992	Andesitic	3	sub-Plinian	264	-	14.5	1,2
Spurr (USA), August 1992	Andesitic	3	sub-Plinian	210	36	14	1,2
Spurr (USA), September 1992	Andesitic	3	sub-Plinian	216	39	14	1,2
Hekla (Iceland), 1970	Andesitic	3	-	120	-	14	2
Hekla (Iceland), 1980	Andesitic	3	-	300	-	15	2
Reventador (Ecuador), 2002	Andesitic	4	-	1320	-	17	2
Hekla (Iceland), 1947 (Brownish-grey ash)	Andesitic	4	-	30	-	28	2
Hekla (Iceland), 1947 (Brownish-black ash)	Andesitic	4	-	30	-	16	2
Soufrière St. Vincent 1902	Andesitic	4	-	150	-	14	2
El Chichón A (Mexico), 1982	Andesitic	5	-	300	-	20	2
El Chichón B and C (Mexico), 1982	Andesitic	5	Plinian	660	870	30	1,2
Hudson (Chile), 1991	Andesitic	5	Plinian	3783	3900	18	1,2
Santa Maria (Guatemala), 1902	Andesitic	6	-	1800	-	34	2
St. Helens (USA), 25 May 1980	Dacitic	3	sub-Plinian	30	42	10	2,4
St. Helens (USA), June 1980	Dacitic	3	sub-Plinian	30	45	9.6	2,4
Pinatubo (Philippines), 12 June 1991	Dacitic	3	-	38	-	17	2
St. Helens (USA), 18 May 1980	Dacitic	5	Plinian	540	630	13	2,4
Quizapu (Chile), 1932	Dacitic	6	Plinian	1080	-	28	2
Novarupta (USA), 1912 (Episode II)	Dacitic	6	Plinian	1560	4800	22	2
Novarupta (USA), 1912 (Episode III)	Dacitic	6	Plinian	600	4000	19	2
Pinatubo (Philippines), 15 June 1991	Dacitic	6	Plinian	540	5700	40	1,2
Puyehue-Cordon Caulle (Chile), June 2011 (Layers A-F)	Rhyolitic	3-4	sub-Plinian	1440	450	12	2,5
Chaitèn (Chile), May 2008 (Phases 1-4)	Rhyolitic	4	sub-Plinian	10083	171	19	2,6
Askja (Iceland), March 1875 (Units B-D)	Rhyolitic	4-5	sub-Plinian to Plinian	480	989	19	4
Novarupta (USA), 1912 (Episode I)	Rhyolitic	6	Plinian	960	4800	23	2,4