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## ► To cite this version:

Pablo Samaniego, Jorge Ordóñez, Mathilde Bablon, Minard Hall, Xavier Quidelleur, et al.. The eruptive chronology of the carihuaairazo volcano (Ecuador): Recurrent sector collapses of a Middle Pleistocene stratovolcano of the northern andes. *Journal of South American Earth Sciences*, 2022, pp.103865. 10.1016/j.jsames.2022.103865 . hal-03689975

**HAL Id: hal-03689975**

**<https://hal.science/hal-03689975>**

Submitted on 22 Jul 2024

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1     **The eruptive chronology of the Carihuairazo volcano (Ecuador): recurrent sector**  
2             **collapses of a Middle Pleistocene stratovolcano of the Northern Andes**

3

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23             *Manuscript submitted to the Journal of South American Earth Sciences*

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25

26 **Abstract**

27 The eruptive chronology of arc volcanoes consists of construction stages usually  
28 punctuated by large collapse events affecting the edifice. In this paper, we reconstruct  
29 the eruptive chronology of Carihuairazo volcano, a Middle Pleistocene edifice from the  
30 Ecuadorian segment of the Andean Northern Volcanic Zone. This study is based on  
31 extensive fieldwork on both the proximal flanks of the volcano and the medial-to-distal  
32 deposits of the nearby Ambato basin, as well as a large dataset of geochronological  
33 ( $^{40}\text{K}$ - $^{40}\text{Ar}$ ,  $^{14}\text{C}$ ) and geochemical (major and trace element) data. The Basal Carihuairazo  
34 edifice is mainly composed of an andesitic lava flow succession dated at 230-200 ka.  
35 The resulting edifice suffered a first sector collapse that was responsible for a relatively  
36 large ( $4 \pm 1 \text{ km}^3$ ) debris avalanche deposit (DAD-1) that covers the entire Ambato  
37 basin. This event occurred between  $206 \pm 4$  and  $216 \pm 5$  ka. Then, Carihuairazo started  
38 a succession of construction (Intermediate and Terminal lava flow successions) and  
39 destruction stages lasting about 50 ky (*i.e.*, from 200 to 150 ka), which are composed by  
40 thick block-and-ash flow deposits (L- and U-BAFD) and debris avalanche deposits  
41 (DAD-2). This volcanic succession is recorded in the Ambato basin, interlayered with  
42 several tephra fallout deposits (TFD-1 to -4) whose source is the neighbouring Huisla-  
43 Mulmul volcanic complex. The current morphology of Carihuairazo results from two  
44 additional sector collapses (DAD-3 and -4) that occurred during the past 40-50 ka, *i.e.*,  
45 following a long period (at least 100 ka) without volcanic activity. We stress these  
46 debris avalanches were not related with magmatic activity. Samples from the  
47 Carihuairazo volcano defines a medium-K magmatic trend composed of andesites and  
48 dacites with a mineral assemblage of plagioclase, amphibole, ortho- and clino-pyroxene,  
49 and Fe–Ti oxides. The evolution of the Carihuairazo edifice, recorded in the medial-  
50 distal deposits of the Ambato basin, represents a unique example in the Ecuadorian arc  
51 of an edifice that experienced successive destruction and construction stages during a  
52 major part of its volcanic history.

53

54 **Keywords:** eruptive chronology, debris avalanche deposits, unspiked K-Ar dating,  
55 Carihuairazo, Ecuador

56

57

## 58 **1. Introduction**

59           The eruptive chronology of composite volcanoes often consists of long-lasting  
60 growth stages punctuated by collapse events affecting a single flank or the entire  
61 edifice. These destabilization events may produce large volcanic landslides that usually  
62 transform into long runout debris avalanches (van Wyk de Vries and Davis, 2015). In  
63 addition, some edifices are capped by lava domes complexes that are intrinsically prone  
64 to gravitationally-controlled collapse events (Calder et al., 2015). The resulting debris  
65 avalanches and dome-collapse deposits, emplaced at medial to distal locations at the  
66 foot of the composite volcanoes, provide a detailed stratigraphic record that can help to  
67 define the succession of construction and destruction stages of stratovolcanoes (Zemeny  
68 et al., 2021). In the Ecuadorian Andean context, volcanic sector collapses often occur  
69 during volcanoes' lifetime, with some well-studied examples for large sector collapses  
70 at Chimborazo (Bernard et al., 2008; Samaniego et al., 2012), Tungurahua (Hall et al.,  
71 1999; Bablon et al., 2018), and Sangay (Monzier et al., 1999; Valverde et al., 2021).  
72 However, there are no detailed studies of volcanoes that experienced recurrent sector  
73 collapses followed by reconstruction episodes involving dome complex activity during  
74 a relatively short time span. This scenario has been described in other edifices such as  
75 Taranaki in New Zealand (Zemeny et al., 2021), Shiveluch in Kamchatka (Belousov et  
76 al., 1999), Colima in Mexico (Robin et al., 1987), or Tutupaca in Peru (Samaniego et  
77 al., 2015; Mariño et al., 2021).

78           The Ecuadorian province of the Andean Northern Volcanic Zone (NVZ) is  
79 characterized by a large number (up to 85) of Late Quaternary volcanic centres  
80 distributed in a quite small arc segment of less than 300 km-long (Fig. 1a). This  
81 volcanic arc results from the subduction of the oceanic Nazca plate below the South  
82 American continental plate (Fig. 1b). The Ecuadorian volcanoes are distributed along  
83 north-south alignments that follow the different morphological units composing the  
84 Ecuadorian Andes: the Western Cordillera, the Inter Andean Valley, the Eastern  
85 Cordillera, and the Sub-Andean zone (Hall et al., 2008). The southern termination of the  
86 NVZ is a triangular-shaped arc segment located in central Ecuador, around the cities of  
87 Ambato and Riobamba, and it includes large volcanic centres such as Chimborazo  
88 (Samaniego et al., 2012), Tungurahua (Hall et al., 1999; Bablon et al., 2018) and  
89 Sangay (Monzier et al., 1999). Based on a regional study, Bablon et al. (2019) proposed  
90 that this part of the NVZ developed during the last 0.6 Ma due to the evolving geometry

91 of the slab below this part of the arc (Yepes et al., 2016; Araujo et al., 2021) and the  
92 activation of major crustal faults (Baize et al., 2020).

93

94 **Figure 1. (a)** The Quaternary Ecuadorian volcanic, including some of the most important edifices (from  
95 Hall et al., 2008) as well as the main active faults (from Alvarado et al., 2014). **(b)** Geodynamical setting  
96 of the Ecuadorian arc. GFZ: Grijalva Fracture Zone; GSC: Galápagos Spreading Center; Ca :  
97 Carihuairazo. Edifices cited in the text (dark grey): (1) Mojanda-Fuya Fuya, (2) Imbabura, (3) Cubilche,  
98 (4) Pichincha, (5) Cotopaxi, (6) Sagoatoa, (7) Chimborazo, (8) Puñalica, (9) Huisla-Mulmul, (10)  
99 Tungurahua, (11) Sangay. Main cities: Q, Quito, I, Ibarra; L, Latacunga; A, Ambato; R, Riobamba.

100

101 The eruptive chronology of the large and most active edifices of the southern  
102 termination of the Ecuadorian arc has been reconstructed during the last two decades  
103 (see references above). However, little is known about other volcanoes, such as  
104 Carihuairazo (78°45'W, 01°24'S, 5018 m above sea level -asl), which is located ~140  
105 km south of the Ecuador's capital city, Quito, and only 20 km south-west of Ambato  
106 (Fig. 1a). This volcano, together with the nearby Chimborazo and Puñalica, are  
107 constructed on top of the Western Cordillera of the Ecuadorian Andes, which is  
108 composed of Cenozoic volcano-sedimentary sequences formed in marine environments,  
109 and younger Miocene and Pliocene continental arc-related volcanic sequences (Hughes  
110 and Pilatasig, 2002; Jaillard et al., 2004).

111 The Carihuairazo volcano overlooks the Ambato basin, a densely populated  
112 tectonic depression forming the central-southern part of the Inter Andean valley. In this  
113 context, reconstructing the eruptive chronology of this edifice represents a crucial step  
114 of any hazard assessment strategy. In this work, we coupled detailed stratigraphic data,  
115 geomorphometric reconstructions, geochronological information and geochemical  
116 analyses to define the eruptive chronology and the construction/destruction stages of the  
117 Carihuairazo volcano during the Middle Pleistocene.

118

## 119 **2. Analytical methods**

120 Several field trips were performed in 2009-2011 and included geological  
121 mapping and sampling of most stratigraphic units, especially for the Ambato basin  
122 distal deposits (Ordóñez, 2012). Additional fieldwork on proximal areas was performed  
123 in 2016-2019. As a result, we now have a large (82) sample array of lavas and tephras  
124 covering most volcanic units that allow us to reconstruct the volcanological evolution of  
125 the Carihuairazo volcano.

126

## 127 **2.1. Major and trace elements whole-rock analyses**

128 Major and trace elements analyses were obtained at the Laboratoire Géosciences  
129 Océan (Université de Bretagne Occidentale, Brest, France) from agate-crushed powders  
130 of 82 new samples spanning the entire volcanic history of Carihuairazo volcano and the  
131 Ambato basin deposits (Table 1). We used an Inductive Coupled Plasma-Atomic  
132 Emission Spectrometer (ICP-AES), following the analytical procedure described by  
133 Cotten et al. (1995). In addition, to proceed with stratigraphic correlations, we also used  
134 published data from the neighbouring Puñalica (Narvaez et al., 2018), Huisla-Mulmul  
135 and Chimborazo volcanoes (Samaniego et al., 2012; Ancellin et al., 2017).

136

## 137 **2.2. Radiometric dating**

138 The chronology of the Middle Pleistocene eruptive activity was established  
139 using the unspiked K-Ar dating technique. Nine new age determinations were obtained  
140 at Geoscience Paris-Saclay (GEOPS) laboratory, which complement the six ages  
141 previously obtained by Samaniego et al. (2012) and Bablon et al. (2019). Lava flows  
142 and juvenile blocks of pyroclastic currents deposits were selected based on their  
143 freshness and low vesicle content. The ages of these samples were calculated by  
144 measuring their potassium and radiogenic argon ( $^{40}\text{Ar}^*$ ) content and using the  $^{40}\text{K}/\text{K}$   
145 ratio and the  $^{40}\text{K}$  radioactive decay constants of Steiger and Jäger (1977). We used the  
146 unspiked Cassinot-Gillot technique applied to groundmass and plagioclase (Cassinot  
147 and Gillot, 1982; Gillot et al., 2006), which is well-suited for Quaternary volcanic  
148 products containing low  $^{40}\text{Ar}^*$  contents, and that has already been successfully applied  
149 in Ecuador (Bablon et al., 2018; 2019; Santamaria et al., 2022), as well as in other  
150 volcanic arcs worldwide (*e.g.*, Germa et al., 2011; Grosse et al., 2018; Lahitte et al.,  
151 2019). The  $^{40}\text{Ar}^*$  content is derived from comparing the  $^{40}\text{Ar}/^{36}\text{Ar}$  ratios of the sample  
152 and the atmosphere. Therefore, the apparent age corresponds to the age of the eruption  
153 when measurements are performed on groundmass, or on juvenile crystals. Otherwise,  
154 the apparent age could be older than the eruption, biased by the inherited or excess  $^{40}\text{Ar}$   
155 trapped in the phenocrysts that were not reset in the magma reservoir before eruption  
156 (*e.g.*, Harford et al., 2002; Samper et al., 2008; Germa et al., 2019).

157 To extract the freshest groundmass, the selected samples were crushed and  
158 sieved in the 80-125 or 125-250  $\mu\text{m}$  size-fraction depending on the size and proportion  
159 of phenocrysts. Groundmass or alternatively plagioclase crystals (*e.g.*, samples 16EQ31  
160 and CAR69; Table 2), were isolated by heavy liquids and magnetic separations to

161 obtain fractions of homogeneous density ( $d_{avg} \approx 2.65$ ). Potassium and argon  
162 measurements were duplicated to check their reproducibility within 1- $\sigma$  uncertainty.  
163 Potassium contents were calculated using reference values of MDO-G (K = 3.510%;  
164 Gillot et al., 1992) and BCR-2 (K = 1.481%; Raczek et al., 2001) standards, and  $^{40}\text{Ar}^*$   
165 contents were routinely checked by measurement of ISH-G (1301-1302 AD; Gillot et  
166 al., 1992) and HD-B1 ( $24.21 \pm 0.32$  Ma; Hess and Lippolt, 1994) standards. More  
167 details about the sample preparation, analytical procedures and uncertainties calculation  
168 are provided in Bablon et al. (2018).

169         Lastly, the Late Pleistocene chronology of the volcanic explosive activity in this  
170 region was constrained by three new radiocarbon ages (Table 3) obtained from charcoal  
171 samples collected from distal deposits of the Ambato basin. These samples were  
172 analysed at the Centre for Isotope Research (CIO, Groningen University, Netherlands).  
173 Before  $^{14}\text{C}$  measurement, samples were examined under a binocular microscope with  
174 the aim of eliminating any potential contaminant such as sand and roots. Then, the  
175 samples were chemically pre-treated to remove contaminants, in order to isolate a  
176 suitable fraction for dating. The performed treatment (referred as “AAA”) consists of  
177 the following steps: (1) acid (HCl) leaching to remove soil carbonate; (2) alkali (NaOH)  
178 leaching to remove humic acids; and, (3) acid (HCl) leaching to remove any “modern”  
179  $\text{CO}_2$  absorbed during the previous steps. Variable amounts of the dried sample were  
180 used to obtain, after combustion, a  $\text{CO}_2$  volume equivalent to at least 1 mg of C. Then,  
181  $\text{CO}_2$  is reduced by  $\text{H}_2$  in the presence of iron powder.  $^{14}\text{C}$  activity is finally measured by  
182 mass spectrometry. The  $^{14}\text{C}$  ages are calculated following the procedure of Mook and  
183 van der Plicht (1999) and corrected for mass dependent effects (isotope fractionation)  
184 using the measured  $^{13}\text{C}/^{12}\text{C}$  ratio.

185

### 186 **2.3. Geomorphological reconstruction**

187         Numerical reconstructions of the temporal evolution of paleo-surfaces were used  
188 to estimate the volume of material emitted during the construction of Carihuairazo  
189 volcano ( $V_c$ ) and the volume of eroded material ( $V_e$ ) since the end of its activity. Such  
190 volumes ( $V = \int_{u.a.} \Delta_Z \times ds$ ) correspond to the elevation difference between the upper  
191 and the lower surfaces encompassing any unit/edifice ( $\Delta_Z = Z_{upper} - Z_{lower}$ ),  
192 integrated over the area ( $ds$ ) of the given unit/edifices (u.a.). Considering the duration  
193 of their respective activity ( $\Delta T_c$ ) and quiescence ( $\Delta T_e$ ) periods, we can then quantify

194 their eruptive (output) and erosion rates ( $OR = \frac{Vc}{\Delta T_c}$  and  $ER = \frac{Ve}{\Delta T_e}$ , respectively). We  
195 extracted the present volcano elevation data from a 30-m SRTM Digital Elevation  
196 Model (DEM), and we used the reconstruction method using the ShapeVolc algorithm  
197 developed in Lahitte et al. (2012) and improved in Bablon et al. (2018) and Dibacto et  
198 al. (2020). The paleo-topography at the end of the construction of Carihuairazo is  
199 modelled from the extrapolation of elevation points extracted from the current crests,  
200 and assumed to belong to non-eroded surfaces. The topography prior to the construction  
201 of Carihuairazo was modelled by extrapolating the present basement elevation around  
202 the volcano, using the conventional kriging algorithm. The volume uncertainty is  
203 defined by the integration of the elementary uncertainty of height differences over the  
204 edifice area (u.a.) as  $\sigma_V = \sigma_Z \times u.a.$ , where the uncertainty of the elevation ( $\sigma_Z$ ) is  
205  $\sigma_Z = \sqrt{\sigma_{Z_{upper}}^2 + \sigma_{Z_{lower}}^2}$ . The average uncertainty of the surface elevation is  
206 estimated to be 200 m for the basement from the error maps generated with kriging  
207 interpolation, and to be 20 m for the surface models, based on the standard deviation of  
208 the elevation dispersion of the surfaces used for extrapolations around the surface  
209 modelled by ShapeVolc reconstruction. Finally, the rate uncertainty is defined as  $\sigma_R =$   
210  $R \sqrt{\left(\frac{\sigma_V}{V}\right)^2 + \left(\frac{\sigma_T}{\Delta T}\right)^2}$ , where  $R$  is the eruptive or erosion rate,  $\frac{\sigma_V}{V}$  the relative uncertainty  
211 of the erupted or eroded unit/edifice volume and  $\frac{\sigma_T}{\Delta T}$  the relative uncertainty of the  
212 duration of the activity or quiescence period, calculated from K-Ar ages uncertainties  
213 (Table 2).

214

### 215 **3. Morphology and structure**

216 Carihuairazo edifice displays a roughly circular basal outline (14-15 km in  
217 diameter) and a summit (5018 m above sea level - asl) located on the south-western part  
218 of the edifice. The asymmetrical shape originates from its location between the Inter  
219 Andean valley to the east and the high-plateau of the Western Cordillera to the west  
220 (Fig. 1-4). As a result, the base of the volcano is located at 3200-3300 m asl in the  
221 eastern side, and 3900-4000 m asl in the western side. Longitudinal valley profiles also  
222 show a higher elevation for rivers located on the western side (*i.e.*, A, I; Fig. 4a, b), and  
223 those of the north-eastern (*i.e.*, C, D, E; Fig. 4a, b), and eastern (*i.e.*, G; Fig. 4a, b) sides,  
224 related to the basement elevation offset. The lower flanks of Carihuairazo (below 4500



225 m asl) show gentle slopes ( $<10^\circ$ ), whereas at higher altitudes an uneven topography  
226 with steep slopes ( $10\text{-}30^\circ$ , Fig. 2a) is observed. The summit zone is characterised by a 1-  
227 2 km-wide east-opened scar that is drained by the Pachanlica valley (Fig. 2b-c, 3). Other  
228 large (200-300 m depth) U-shaped glacial valleys with steep sides and flat bottom have  
229 also been carved around the edifice (Fig. 4c), containing arcuate, 2-3 km-long, 100-200  
230 m-high outer and/or terminal moraines (Fig. 2d). In addition, just to the north of the  
231 Pachanlica valley, the Puñalica volcano (3988 m asl), a small (400-600 m-high), young-  
232 looking cone (Fig. 1, 2e) stands on the remnants of the lower north-east flank of  
233 Carihuairazo. Puñalica has a basal diameter of *c.* 3-4 km and a summit slightly  
234 elongated in a NW-SE direction, that includes several coalescent craters. Glacial erosion  
235 did not affect Puñalica, suggesting a post-glacial age younger than the Last Glacial  
236 Maximum (LGM).

237 From the morphology of the Chimborazo and Carihuairazo volcanoes, different  
238 authors (Clapperton, 1990; Samaniego et al., 2012) identified three successive groups of  
239 moraines that were assigned to the LGM, the Younger Dryas (YD) and the younger  
240 Neo-Glacial (NG) periods. At Carihuairazo, the oldest moraines extended down to  
241 3200-3300 m asl in the northern and eastern flanks. Based on  $^{14}\text{C}$  ages obtained from  
242 peat layers under and overlying these moraines, Clapperton (1990) proposed an age  
243 ranging between *ca.* 33 and 14 ka for the LGM moraines in this part of the Andes.  
244 Recently, Bablon et al. (2019) dated a lava sample from Chimborazo volcano (Guano  
245 lava flows of Samaniego et al., 2012) that yielded an age of  $30 \pm 3$  ka (sample 16EQ43).  
246 This lava unit is covered by thick moraine deposits interpreted by Samaniego et al.  
247 (2012) as associated with the LGM period. Based on this evidence, we conclude that the  
248 moraines ascribed to the LGM in this part of the Andes are younger than  $30 \pm 3$  ka,  
249 roughly corroborating the age range proposed by Clapperton (1990). Other intermediate  
250 moraines are radially distributed around Carihuairazo forming sequences of 3-4 arcuate  
251 moraines reaching 3700-3900 m asl (Fig. 2d). Whether or not this intermediate moraine  
252 sequence corresponds to the Younger Dryas period is beyond the scope of this study.  
253 However, our observations suggest that many glacial advances occurred in this part of  
254 the Andes between 30 and 10 ka.

255 Interestingly, a conspicuous break-in-slope is observed at about 3700-3900 m in  
256 the glacial valleys on the north, south and south-east flanks of the volcano (see Fig. 3,  
257 4b). This morphological change is interpreted as resulting from the lower limit of  
258 glacial erosion associated with the LGM. Lastly, above 4400-4500 m asl, we observed

259 smaller moraines that, following Clapperton (1990), should correspond to the Holocene  
260 glacial advances (the so-called Neo-Glacial period).

261

262

263 **Figure 2.** Panoramic views of the Carihuairazo volcano. The view directions are shown in Fig. 3. **(a)**  
264 View from the west showing the Carihuairazo basal lavas and the summit lavas and breccias. **(b)** View  
265 from the east, showing the Pachanlica valley which is partially filled with the post-glacial deposits related  
266 to the 1698 CE mudflow. **(c)** Oblique aerial view from the north, showing the Carihuairazo summit, the  
267 Pachanlica valley and the remnants of the last sector collapse that affected the north-western flanks of  
268 Carihuairazo (red dashed line). DFD: debris flow deposits. **(d)** Quebrada Chiquicahua valley at the  
269 northern flank of Carihuairazo. This deep valley was probably formed during the LGM glaciations. At  
270 least three moraines crop out in the valley's flank, probably associated with the YD period (white dashed  
271 lines). Note also the 1698 CE mudflow deposits at the valley's bottom and the small escarpment along the  
272 valley (black dotted line). **(e)** The young-looking Puñalica cone was constructed on top of old volcanic  
273 deposits and LGM moraines.

274

## 275 **4. Volcanic stratigraphy of Carihuairazo volcano**

### 276 **4.1. The Carihuairazo edifice**

277 **Old lava domes.** Two isolated, highly eroded lava domes crop out on the northern flank  
278 of the volcano, 8 km from the current summit (*e.g.*, Sunantza and Cruz Maqui; dark  
279 green unit, Fig. 3). Their morphology suggests that they are older structures that are not  
280 associated with the adjacent NE-elongated crests of the Yanasacha sector (Fig. 3). A K-  
281 Ar age obtained from the Sunantza andesitic lava dome yielded an age of  $512 \pm 9$  ka  
282 (CAR14, Bablon et al., 2019). Based on this age and the morphological information, we  
283 argue that these pyroxene-bearing siliceous andesitic (59.6-63.0 wt.% SiO<sub>2</sub>) lava domes  
284 correspond to the oldest volcanic unit of the Carihuairazo edifice.

285

286 **Basal lava flows.** This unit comprises a succession of massive (50-80 m-thick) lava  
287 flows from the northern, western, and southern flanks of Carihuairazo, roughly from the  
288 base of the volcano up to 4500-4600 m asl (dark brown unit, Fig. 3). This unit consists  
289 of a 400-600 m-thick andesitic lava pile (59-61 wt.% SiO<sub>2</sub>). The oldest ages from this  
290 unit correspond to the thick lava flows of the lower south-west (Loma Piedra Negra)  
291 and south-east flanks that yielded <sup>40</sup>Ar/<sup>39</sup>Ar plateau ages ranging from about 200 to 230  
292 ka (Fig. 3; Samaniego et al., 2012), with two samples from the south-east flank dated at  
293  $221 \pm 5$  and  $224 \pm 5$  ka (RIO117 and RIO118, respectively), and two samples from the  
294 south-west flank dated at  $213 \pm 5$  and  $208 \pm 10$  ka (RIO87A and B, respectively). These  
295 basal lava flows form the Abraspungo saddle between Carihuairazo and Chimborazo  
296 volcanoes. In the upper proximal zone, the oldest age corresponds to a lava flow  
297 intercalated on a lava flows and breccia succession that forms the inner scar wall, in the

298 north-east flank of the edifice. This andesitic lava flow, dated here at  $217 \pm 9$  ka  
299 (16EQ45, Table 2; Fig. 3), is undistinguishable from the previously mentioned  
300  $^{40}\text{Ar}/^{39}\text{Ar}$  ages from the outer flanks.

301

302 **Chibuleo block-and-ash-flow deposits.** In the northern part of the volcano, the flat  
303 surfaces of Chibuleo, Pilahuin, and Tambo Loma are made of a thick succession of  
304 several block-and-ash-flow deposits that rest on the Carihuairazo Basal lava flows and  
305 on the Plio-Quaternary volcanic sequence exposed on the Río Ambato valley (dark  
306 yellow unit, Fig. 3). These reddish-grey, structureless deposits have individual  
307 thicknesses of 10-15 m, and are composed of large blocks (>1-2 m in diameter) within a  
308 sand-rich matrix (60-70 vol.%). The juvenile blocks are amphibole-bearing siliceous  
309 andesites (60.8-62.8 wt.%  $\text{SiO}_2$ ). This block-and-ash-flow succession was likely  
310 produced during a large dome-forming phase at Carihuairazo, whose dome remnants  
311 were not identified. This unit is overlain by a thick (up to 50 m) succession of  
312 weathered tephra fallout deposits with intercalated, partially indurated and reworked  
313 ash-rich layers (locally named Cangahua). At the base of this tephra fallout succession,  
314 we identified a 1-m-thick pumice-rich layer that consists of white, rhyolitic pumice  
315 erupted from the Huisla-Mulmul volcanic complex (TFD-1, see below).

316

317 **Figure 3.** Geological sketch map of the Carihuairazo volcano, including the location of the new (white)  
318 and previous (grey) dated samples (ages in ka). Previous ages come from Samaniego et al. (2012) and  
319 Bablon et al. (2019). Grey colours for surrounding areas: dark grey for the Mio-Pliocene volcanic  
320 sequences, light grey for neighbouring volcanoes. The points of view refer to Fig. 2.

321

322 **Figure 4.** (a) Shaded relief view of the 4-m DEM of Carihuairazo and Puñalica volcanoes, with main  
323 rivers highlighted by different colours. (b) Longitudinal profile of rivers plotted from the high point of the  
324 Carihuairazo elevation model at the end of its construction. Same colours as Fig. 4a. (c) Transverse  
325 profile of rivers. Cross sections and associated colours are indicated in Fig. 4a. (d) Shaded relief view  
326 showing the elevation of crests used to compute paleo-topographies of the volcano.

327

328 **Intermediate lava flows and breccias.** This unit is composed by a thick succession of  
329 lava flows and breccias conforming the outer western and south-western flanks, above a  
330 marked break-in-slope at around 4500 m asl (light green unit, Fig. 3). These thick  
331 andesitic lavas overlay the Basal lava flows (*i.e.* Piedra Negra). We obtained two  
332 similar ages of  $199 \pm 5$  and  $198 \pm 7$  ka (16EQ49 and 16EQ51, respectively; Table 2)  
333 from this lava flow succession, which are slightly younger than the previously described  
334 Basal lava flows. This intermediate unit is also formed by the monotonous lava flow  
335 succession conforming the north-eastern crests (*i.e.* Yanasacha) located between the

336 Quebrada (ravine) Chiquichua and Quebrada Quichibi. Two similar ages were  
337 obtained from the north-eastern ( $197 \pm 4$  ka, groundmass age of 16EQ31; Table 2) and  
338 northern flanks ( $186 \pm 5$  ka; CAR69; Table 2 and Fig. 2a-b, and 3). Note that 16EQ31  
339 sample was also dated at  $187 \pm 9$  ka on plagioclase crystals. However, because their K  
340 content is four times lower than that of the groundmass, we only consider here the best-  
341 constrained age of  $197 \pm 4$  ka. We stress these ages are slightly younger than that of the  
342 Basal lava flows succession ranging from  $224 \pm 5$  to  $208 \pm 10$  ka (Samaniego et al.,  
343 2012).

344 We include in this unit the non-continuous, heterogeneous, hydrothermally-  
345 altered lavas and breccias successions cropping out along the Pachanlica valley (*i.e.*  
346 Milincocha hill). We interpret this sequence as a series of “toreva” megablocks  
347 associated with the first large sector collapse that affected the Carihuairazo (DAD-1, see  
348 below; Fig. 3).

349

350 **Terminal lava flows.** The upper remnants of the Carihuairazo cone are composed of a  
351 succession of amphibole-bearing andesitic (59-60 wt.% SiO<sub>2</sub>) lava flows with  
352 interlayered breccias (light brown-red unit, Fig. 3). Two ages were obtained on this  
353 succession, yielding ages of  $172 \pm 7$  and  $157 \pm 5$  ka (16EQ50 and 16EQ48,  
354 respectively; Table 2). Compared with the Basal/Intermediate lava flows, this lava  
355 succession displays higher slopes that mark a clear angular discordance. However,  
356 given the lack of a conspicuous erosional discordance between the Basal and  
357 Intermediate lava flows units and the Terminal lava flows, and the overlapping  
358 radiometric ages for Intermediate and Terminal units, we propose that the construction  
359 of the Terminal edifice followed the Intermediate lavas by only a few thousands of  
360 years.

361 We include in this unit the amphibole-bearing dacitic domes (Santa Rosa,  
362 Cahuito and Pitiunga) that crop out on both sides of the Pachanlica valley (Fig. 2c, 3).  
363 An additional age was obtained from the Pitiunga dome, yielding an age of  $176 \pm 10$  ka  
364 (CAR60, Table 2) which is identical to that of the lavas from the upper remnants of  
365 Carihuairazo.

366

#### 367 **4.2. Stratigraphy of the Ambato basin**

368 In this section we describe in a stratigraphic order, the debris avalanche and the  
369 pyroclastic currents deposits of the Ambato basin. Based on stratigraphic and

370 morphological considerations, as well as geochemical characteristic of the juvenile  
371 products (see below), these deposits originated from the Carihuairazo volcano. We also  
372 describe the regional tephra fallout deposits that are interlayered in this volcanic  
373 succession. The Ambato basin volcanic succession overlies the Quaternary volcano-  
374 sedimentary deposits of the Inter Andean valley (the so-called Latacunga Formation,  
375 Lavenu et al., 1992) and the Chalupas ignimbrite deposits (Beate et al., 2006). It is  
376 worth noting that Bablon et al. (2019) obtained an age of  $799 \pm 12$  ka for a lava flow  
377 from the Sagoatoa volcano, which is interlayered in the volcanoclastic deposits of the  
378 Latacunga Formation. In addition, the Chalupas ignimbrite deposits were recently dated  
379 at  $216 \pm 5$  ka (Bablon et al., 2020). These ages, especially that of Chalupas deposits,  
380 represent the oldest bound for the Carihuairazo deposits in the Ambato basin. The  
381 detailed stratigraphic sections throughout the Ambato basin, and some key photos of the  
382 main units are shown in Fig. 5 and 6; whereas the synthetic stratigraphy of the Ambato  
383 basin is presented in Fig. 7.

384

385 ***Debris avalanche deposit 1 (DAD-1)***. This unit is exposed in the Ambato basin, from  
386 J.B. Vela to the west to the Totoras town to the east, mostly on the south side of the Río  
387 Ambato valley (Fig. 3). This deposit has a maximum runout of 25 km from its supposed  
388 source region on the upper flanks of Carihuairazo. Its south-east limit is not well  
389 constrained given that the younger lava flows from the Puñalica volcano overlay the  
390 DAD-1 south of Quebrada Catequilla (Fig. 3, 6). The greatest thickness was observed in  
391 the south-eastern part of the Ambato basin, reaching 25-40 m along the Río Mocha  
392 valley. In contrast, in the north and north-eastern limit, the maximum observed  
393 thickness are of 5-10 m. Assuming an average thickness of  $20 \pm 5$  m over about 200  
394 km<sup>2</sup> (Fig. 8), the volume of DAD-1 is estimated at  $4 \pm 1$  km<sup>3</sup>.

395 The DAD-1 unit is composed of a massive, heterogeneous, polymictic breccia  
396 that, following the terminology of Glicken (1991), is composed of two facies deposits.  
397 The block facies consist of large (up to 2 m in diameter), highly cataclased blocks with  
398 abundant jigsaw cracks and fractures included in a sandy matrix. Lava blocks are  
399 mostly unaltered andesites with a mineral assemblage composed of plagioclase,  
400 pyroxenes, and amphibole, with some scarce hydrothermally-altered andesitic blocks.  
401 The mixed facies is composed of heterogeneous, beige, sand-rich interclast matrix (70-  
402 80 vol.%), with heterogeneous blocks (up to 20 cm in diameter) of similar composition  
403 than those from the block facies. The mixed facies is mainly observed at the lower part

404 of the deposit. This unit overlays the volcanoclastic sediments of the Latacunga  
405 Formation, and the Chalupas ignimbrite deposits. This unit is covered by a thick  
406 rhyolitic tephra fallout deposit (TFD-1) and the lower block-and-ash flow deposits (L-  
407 BAFD) (Fig. 6).

408

409 **Figure 5.** (a) Bellavista quarry shows an almost complete cross-section for the Ambato basin. (b) La  
410 Peninsula, Rio Ambato valley. Contact between the Chalupas ignimbrite deposit and the DAD-1. (c) San  
411 Vicente quarry. (d) Juvenile block (with prismatic jointing) in the L-BAFD, San Vicente quarry. This  
412 block was dated by the K-Ar method (16EQ51, Table 2). (e) El Carmen quarry. (f) Small quarry on the  
413 Paso Lateral. Locations are indicated in Fig. 6, and abbreviations are detailed in Fig. 7 and in the text.

414

415 **Lower block-and-ash-flow deposits (L-BAFD).** In the north-western part of the  
416 Ambato basin, we observe a 100-300-m-high, NE-SW elongated relief made by the  
417 Casigana and Bellavista hills (Fig. 3). At the Bellavista and San Vicente quarries (Fig.  
418 5, 6), this unit consists of at least three, 3-6 m-thick layers, of a matrix-supported (70-80  
419 vol.%), monolithological breccia composed of angular blocks (up to 50-80 cm in  
420 diameter) included into a sandy, grey to reddish matrix. Juvenile blocks from these  
421 deposits are amphibole-bearing siliceous andesites (62-63 wt.% SiO<sub>2</sub>). The upper half of  
422 each layer displays a reddish colour whereas the lower half mostly displays grey colour.  
423 Small charred organic material on this deposit that yielded <sup>14</sup>C age older than the  
424 method limit (>45 ka, Table 3). K-Ar dating of a juvenile prismatically-jointed block  
425 from this unit yielded an age of 206 ± 4 ka (17EQ115, Fig. 5d, Table 2). These block-  
426 and-ash-flow deposits are likely associated with the growth of a dome complex in the  
427 summit area. This unit is interlayered between the DAD-1 and the intermediate DAD-2  
428 (see below; Fig. 6 and 7). Its upper and lower contacts are concordant, suggesting a  
429 deposition with a short lifespan between each unit.

430

431 **Debris avalanche deposit 2 (DAD-2).** This unit crops out at the north-western  
432 (Bellavista and San Vicente quarries) and south-eastern (El Carmen quarry) sides of the  
433 Ambato basin (Fig. 6). Because of its intermediate stratigraphic position, outcrops are  
434 scarce and we cannot fully define its geographical extension. Its thickness varies from  
435 5-6 m up to 12 m across the Ambato basin, which should be considered as minimum  
436 values as its base was often not observed. Ordóñez (2012) proposed an area of 100 km<sup>2</sup>  
437 (Fig. 8), and, assuming an average thickness of 5-10 m, we propose a volume range of  
438 0.5-1.0 km<sup>3</sup>. Despite this rough estimation, DAD-2 exhibits a volume notably smaller  
439 than the older DAD-1. This unit overlies the TFD-1 (Totoras log, Fig. 6) and the lower

440 block-and-ash flow unit (Bellavista log, Fig. 6), and it is covered by a tephra fallout  
441 deposit (TFD-2; El Carmen log, Fig. 6) and/or the upper block-and-ash flow unit (U-  
442 BAFD, Bellavista log, Fig. 6).

443 DAD-2 is a heterogeneous breccia showing a characteristic patchwork pattern,  
444 consisting of block facies immersed in a mixed facies (Fig. 5, 6). The block facies  
445 consists of large (up to 1-2 m in diameter), variably cataclased blocks with frequent  
446 jigsaw cracks and fractures immersed in a sandy matrix. Lava blocks are mostly  
447 unaltered andesites with a mineral assemblage composed of plagioclase, pyroxenes, and  
448 amphibole. The mixed facies is composed of heterogeneous, beige, sand-rich interclast  
449 matrix (60-70 vol.%), with primarily angular andesitic blocks (up to 20 cm in diameter)  
450 and some scarce pumice fragments from the lower TFD-1 horizon.

451

452 **Figure 6.** Key stratigraphic columns in the Ambato basin.

453

454 ***Upper block-and-ash-flow deposits (U-BAFD).*** This unit crops out in the basin's north-  
455 western side, at Bellavista and San Vicente quarries (Fig. 6, 7). This 6-8 m-thick unit is  
456 a matrix-supported (70-80 vol.%), monolithological breccia composed of angular blocks  
457 (up to 1-2 m in diameter) immersed in a sand-rich matrix with the characteristic grey-  
458 reddish colour. Juvenile blocks from this unit are amphibole-bearing siliceous andesites  
459 (62-63 wt.% SiO<sub>2</sub>). This unit is concordant above the previously described DAD-2 and  
460 is covered by a tephra fallout deposit (TFD-2, El Carmen log, Fig. 6) and a younger  
461 debris avalanche deposit (DAD-3, logs San Vicente and Bellavista, Fig. 6). At El  
462 Carmen quarry, the upper part of U-BAFD grades into a 20-30 cm-thick, dark grey, ash-  
463 rich layer, interpreted as a paleosoil (see below). This paleosoil horizon is associated  
464 with an unconformity representing a period without volcanic deposition in the Ambato  
465 basin.

466

467 ***Debris avalanche deposit 3 (DAD-3).*** This unit is widely distributed in the Ambato  
468 basin. Good exposures occur along the main drainages (Fig. 3), *i.e.* the Quebradas  
469 Catequilla and Terremoto, and the Río Ambato and Río Pachanlica valleys, with a  
470 maximum runout of 25 km in the NE direction (DAD-3; Fig. 8). The observed thickness  
471 ranges from 2-5 up to 15-20 m. It covers an area of 100-110 km<sup>2</sup>, quite similar to that of  
472 the DAD-2. The average thickness of 8-10 m leads to an estimated volume of ~1 km<sup>3</sup>, a  
473 value similar to the DAD-2 and notably lower than DAD-1. This deposit is massive

474 with no gradation structure. It is a heterogeneous, polymictic breccia, with the two  
475 typical facies observed in the previously described DADs. The block facies consists of  
476 large (up to 5 m in diameter), highly cataclased blocks with abundant jigsaw cracks and  
477 fractures immersed in a sandy matrix. Some scarce megablocks (200-250 m long and  
478 20-50 m high) were observed and mainly consist of block facies. Lava blocks are  
479 mostly unaltered andesites with a similar mineral assemblage to those of the previously  
480 DADs. The mixed facies is composed of heterogeneous, beige, silty-sandy interclast  
481 matrix (75-85 vol.%), with heterogeneous blocks (up to 20 cm in diameter) of similar  
482 composition than in the block facies. The dominant mixed facies includes patches of the  
483 block facies. Lastly, a third, transitional facies was observed at the NE distal parts (e.g.,  
484 Totoras). This polymictic deposit is characterised by a beige sandy-silty interclast  
485 matrix (50-65 vol.%) and includes subrounded blocks of andesitic composition. The  
486 matrix is consolidated and includes frequent millimetric-size bubbles. Based on these  
487 characteristics, and following the criteria summarized by Harpel et al. (2011), we  
488 interpret this subunit as a lahar deposit associated with the main debris avalanche  
489 deposit. The DAD-3 unit is interlayered between U-BAFD and TFD-2 units below and  
490 the TFD-3 unit above (Fig. 6).

491

492 **Figure 7.** Synthetic stratigraphy of the Ambato basin.

493

494 **Figure 8.** Debris Avalanche Deposits distribution in Ambato basin.

495

496 ***Debris avalanche deposit 4 (DAD-4).*** This unit is the youngest debris avalanche deposit  
497 of the Carihuairazo volcano. Contrary to the previous debris avalanche deposits that  
498 spread over a wide area of the Ambato basin, this unit is channelized along the Pataló,  
499 Terremoto and Catequilla valleys (Fig. 8). Its thickness is lower than the previous  
500 deposits, ranging from 1 to 5 m in the distal zone, and 8-12 m in the proximal zone (log  
501 2, Río Pataló, Fig. 6). Ordóñez (2012) proposed an area of 65-70 km<sup>2</sup> for DAD-4 (Fig.  
502 8), and assuming an average thickness of 2-3 m, we estimate a volume of 0.15-0.20  
503 km<sup>3</sup>.

504 This unit is a massive, polymictic, matrix-supported breccia composed of 10-20  
505 vol.% of blocks, whose size ranges from 5 and 80 cm in diameter, although larger  
506 blocks (up to 1-2 m) were also observed. Blocks are primarily angular or subangular,  
507 with frequent jigsaw fractures, especially in larger blocks. The silt-rich matrix is



508 commonly beige-brown, although in some cases, red-grey colours are also observed,  
509 and display frequent millimetric-size bubbles, especially at the base of the deposit.  
510 Blocks are primarily pyroxene-rich and amphibole-bearing andesites, mostly unaltered,  
511 although hydrothermally-altered blocks were also observed. The poly lithologic nature  
512 of the blocks, the matrix's characteristics, and the presence of block facies patches with  
513 jigsaw fractures, point to a cohesive lahar deposit that was generated from a debris  
514 avalanche.

515 This unit rests on top of the Ambato basin volcano-sedimentary succession (Fig.  
516 6, 7). Given that the glacially-formed valleys channelized this debris avalanche, we  
517 suggest that the age of the DAD-4 is younger than the LGM event.

518

519 ***Huisla-Mulmul tephra fallout deposits.*** One of the main features of the Ambato basin  
520 stratigraphic succession is the presence of 4 major tephra fallout deposits (here named  
521 as TFD-1 to -4), which are interlayered with the debris avalanche and block-and-ash-  
522 flow deposits from Carihuairazo volcano (Fig. 6, 7). The isopach maps presented by  
523 Ordóñez (2012) show thickness decreasing from the SE towards the NW of the Ambato  
524 basin (Fig. 9, 10), pointing to the Huisla-Mulmul volcanic complex as the potential  
525 source. This interpretation is supported by geochemical data (Fig. 11) of the juvenile  
526 pumice fragments from these deposits that define a regular trend with the lavas sampled  
527 in these edifices (see below). We summarize below the main characteristics of these  
528 deposits.

529

530 ***Tephra fallout deposit 1 (TFD-1).*** This layer crops out in the entire Ambato basin, with  
531 thickness from 3-5 m at Totoras, close to Huisla volcano, to less than 1 m at Ambato-  
532 Izamba and Chibuleo cross-sections (Fig. 9). This deposit is composed of white, highly  
533 vesiculated, crystal-poor (< 5 vol.%) pumice fragments (80-85 vol.%) of biotite-bearing  
534 rhyolitic composition (73-77 wt.% SiO<sub>2</sub>), and distinctive metamorphic (mostly  
535 greenschist) lithic fragments (10-15 vol.%) belonging to the Alao-Paute Formation of  
536 the Eastern Cordillera basement (Aspden and Litherland, 1992). A minor component  
537 (~5 vol.%) corresponds to reddish-grey, dense andesitic lithics. At proximal zones (*i.e.*,  
538 Totoras; Fig. 3), this unit is well stratified, allowing to identify four different subunits  
539 with transitional contacts, defined by grain size, lithic contents, lamination and  
540 gradation (Fig. 10a). This unit represents one of the main tephrochronological markers  
541 for this part of the Inter Andean valley. Based on 16 thickness measurements and using

542 the formulation of Pyle (1989), Ordóñez (2012) estimated a minimum volume of 1.2  
543 km<sup>3</sup> corresponding to an eruption with a Volcanic Explosive Index (VEI) of 5.

544  
545 **Figure 9.** Isopach maps for the tephra fallout deposits of the Ambato basin (modified from Ordóñez,  
546 2012). We stress that no enough data could be gathered to draw an isopach map for TFD-2.  
547

548 *Tephra fallout deposit 2 (TFD-2).* This layer crops out in the eastern part of the Ambato  
549 basin, between Totoras (1.5 m-thick) and Ambato-Izamba (0.5-0.15 m-thick; Fig. 9). It  
550 comprises white, moderately vesiculated pumice fragments (up to 90-95 vol.%) of  
551 rhyolitic composition (72-73 wt.% SiO<sub>2</sub>), with crystals (5-10 vol.%) of plagioclase,  
552 biotite, amphibole, and minor amounts of pyroxenes and magnetite. Additionally, some  
553 (5-10 vol.%) hydrothermally-altered lithics, and andesitic fragments were also observed  
554 at the unit's base. The base of this deposit is made of a centimetric thick coarse ash  
555 layer grading to the main tephra deposit, which shows a normal gradation at the base  
556 and a reverse gradation at the top. This layer is interpreted as a pyroclastic surge deposit  
557 (Fig. 10c-d) that overlies the previously described 20-30 cm-thick paleosoil. The surge  
558 layer includes some small charred twigs (Fig. 10c-d), which were dated twice by  
559 radiocarbon at 39 ± 0.4 ka and >45 ka (Table 3). Because of the scarcity of outcrops, we  
560 cannot elaborate an isopach map for the TFD-2.

561  
562 **Figure 10.** Stratigraphic relationships between DAD and TFD. **(a)** TFD-1 overlying DAD-1 at Coco-Cola  
563 cross-section (point 9 in Fig. 6). BF – bloc facies, MF – matrix facies. **(b)** TFD-3 and 4 and the A-TFD at  
564 Palahua cross-section (point 7 in Fig. 5). **(c)** TFD-2 and DAD-3 in El Carmen outcrop (point 3 in Fig. 6).  
565 Note the paleosoil at the base of the TFD-2 and at the top of a reworked U-BAFD horizon. **(d)** Close-up  
566 of El Carmen outcrop. **(e)** DAD-4 overlaid by the distal andesitic tephra fallout deposits, whose origin is  
567 probably Chimborazo volcano. Note the presence of the “bicolour layer”. **(f)** Distal andesitic tephra  
568 fallout deposits at Tisaleo – J.B. Vela road.  
569

570 *Tephra fallout deposit 3 (TFD-3).* This layer crops out in the entire Ambato basin, with  
571 thickness from 1.2 m at Totoras, to less than 0.2 m at its north-western border. This  
572 deposit comprises white, moderately vesiculated, crystal-rich (25-30 vol.%) pumice  
573 fragments of high-silica dacitic composition (68-70 wt.% SiO<sub>2</sub>). It contains phenocrysts  
574 of plagioclase, biotite, amphibole, pyroxenes and magnetite. Some pumice fragments  
575 display roughly banded textures between two end-members of light grey and white  
576 colours. We note that no chemical heterogeneity has been identified pointing to textural,  
577 instead of chemical, differences between both end-members. The deposit is  
578 homogeneous, without lamination, excepting the several centimetres thick, coarse ash  
579 layers found at the base and top of the unit. Ordóñez (2012) estimated a minimum

580 volume of 0.2 km<sup>3</sup> (based on 20 thickness measurements) that corresponds to an  
581 eruption with a volcanic explosive index (VEI) of 4.

582

583 **Figure 11.** Selected major and trace elements *versus* silica content for proximal eruptive products of  
584 Carihuairazo volcano as well as the distal deposits of the Ambato basin. We show also for comparison  
585 purposes the eruptive products of the neighbouring Puñalica (Narvez et al., 2018) and Huisla-Mulmul  
586 (Ancellin et al., 2017) volcanic centres.

587

588 *Tephra fallout deposit 4 (TFD-4).* The TFD-4 crops out in the entire Ambato basin (Fig.  
589 9), although its thickness are lower than the previous tephra fallout deposits, ranging  
590 from 0.5 m on the lower Huisla flank, to 0.15-0.2 m in Ambato. This deposit comprises  
591 three subunits. The lower one is a homogenous, fine-medium sized, ash fallout deposit  
592 with a normal grading. This layer evolves upwards to a well-laminated, ash-rich  
593 horizon. Then, the upper layer, which is the thickest and has a wide geographical  
594 distribution, is composed of pumice-rich lapilli and coarse ash with a normal gradation.  
595 All three layers contain similar crystal-rich (15-25 vol%) white-beige pumice fragments  
596 with a mineral assemblage composed of plagioclase, amphibole, biotite, pyroxenes, and  
597 Fe-Ti oxides, and dense lithic fragments of grey and reddish-grey andesites. Ordonez  
598 (2012) estimated a minimum volume of 0.1 km<sup>3</sup> for this deposit (21 thickness  
599 measurements), leading to a VEI of 4.

600

601 *Other undifferentiated tephra fallout deposit (U-TFD).* Above the TFD-4 deposit, we  
602 observe a succession of at least eight tephra fallout deposits that are interlayered with  
603 beige-brown, weathered, partially indurated and reworked ash layers (i.e. Cangahua).  
604 The overall thickness is of 2-3 m, and individual thicknesses are of about 10-40 cm at  
605 the Totoras outcrop. These lapilli-rich layers show a decrease in the grain size and  
606 thickness from north to south. They are composed of grey to dark brown, andesitic  
607 scoria fragments, grading from coarse scoria to lapilli (up to 5 cm in diameter). We are  
608 unable to draw individual isopach maps for these deposits, however, based on the grain  
609 size and some scarce geochemical data (not shown), we propose the Huisla-Mulmul  
610 volcanic complex as their source. This sequence is covered by the DAD-4 (Fig. 5f,  
611 10b).

612

613 *Distal andesitic tephra fallout deposits (A-TFD).* At least eight tephra fallout deposits  
614 crop out in the western part of the Ambato basin, between Mocha, Tisaleo and J.B. Vela

615 towns (Fig. 3). These tephra fallout deposits are composed of dense, dark-brown,  
616 andesitic (56.5-58.5 wt.% SiO<sub>2</sub>) scoria with minor amounts of dense, lithic fragments.  
617 These deposits are interlayered with reworked ash layers with disseminated scoria  
618 fragments and often transitional contacts between tephra and ash horizons. The total  
619 succession is 7-8 m thick, with individual scoria layers ranging from 5 to 50 cm in the  
620 Mocha – J.B. Vela road (Fig. 10f). The thickness of these layers regionally decreases  
621 toward the north-east of the Ambato basin, whereas these layers are absent to the west,  
622 above 3400-3600 m. Although a detailed study of these layers is beyond the scope of  
623 this study, geochemical data from scoria fragments suggest that these tephra layers have  
624 been emitted by the nearby Chimborazo volcano (Fig. 12, see below). In the middle-  
625 lower part of this succession, we observed a key horizon consisting of two fallout layers  
626 of almost similar thickness (between 10 and 15 cm thick). The lower one consists of  
627 dark grey-brown scoria with scarce altered lithics (2 cm maximum) and the upper one  
628 consists of light grey-beige scoria (4 cm maximum) with scarce non-altered, andesitic  
629 lithics. We interpret this double layer as corresponding to the Chimborazo volcano key  
630 horizon “III” (Samaniego et al., 2012). Given that this horizon covers glacial deposits  
631 interpreted as formed during the Last Glacial Maximum, we propose an age younger  
632 than 20-30 ka. This tephra succession, including the bicolour layer, covers the DAD-4  
633 (Fig. 10e-f).

634

635 ***The Puñalica volcano.*** This lava-dominated cone is composed of a succession of lava  
636 flows that are unaffected by glacial erosion. These lavas extend up to 10-11 km towards  
637 the north-east, up to the Río Mocha valley and Cevallos town (Fig. 3). These lavas  
638 cover the succession of distal andesitic tephra fallout deposits (A-TFD, Fig. 10f).  
639 Puñalica lavas are mostly basaltic andesites and andesites (55-60 wt.% SiO<sub>2</sub>) with a  
640 mineral assemblage composed of plagioclase, ortho- and clino-pyroxene, and frequent  
641 olivine phenocrysts. Some of these samples were described by Narvaez et al. (2018).

642 The upper part of Puñalica is composed of proximal lava flows and pyroclastic  
643 fallout deposits (54-56 wt.% SiO<sub>2</sub>) cropping out on its upper south-east flank. These  
644 deposits correspond to lithic-rich centimetric-to-decimetric size layers covering the  
645 youngest lava flows. At the southern part of the cone, in the Quebrada Olalla valley  
646 (Fig. 3), these deposits represent a succession of several 10 to 50 cm-thick layers  
647 composed of juvenile scoria bombs and dense prismatic-jointed blocks (up to 30 cm  
648 in diameter) of andesitic composition (54-58 wt.% SiO<sub>2</sub>). Field relationships of the

649 Puñalica lavas and moraine deposits in the Río Pachanlica valley to the south of the  
650 cone allowed Clapperton (1990) to postulate that the activity of this cone occurred  
651 between 18 and 14 ka. This assumption was corroborated by a K-Ar age obtained from  
652 a distal lava sample of Puñalica that yielded an age of  $18 \pm 3$  ka (RIO18; Bablon et al.,  
653 2019). This datation supports a pre-Holocene age for the oldest Puñalica lavas.

654

655 ***The 1698 CE debris flow deposit.*** The youngest deposit cropping out in the quebradas  
656 draining the Carihuairazo massif (*i.e.*, Chiquichagua, Pataló, Quichibí, Terremoto,  
657 Catequilla and Pachanlica-Olalla-Mocha; Fig. 3) is a 2-4 m-thick, dark, matrix-rich  
658 deposit composed by fine sand and silt materials, with some scarce 10-40 cm rounded  
659 blocks (Vásconez et al., 2009; Vasconez et al., 2019). One of the most conspicuous  
660 characteristics of this deposit is the presence of subvertical prismatic, which were  
661 interpreted as desiccation cracks implying that this deposit was water-saturated. This  
662 deposit forms flat terraces on the valley floor and in the medial to distal zones (Ambato  
663 basin; Fig. 2c), and covers the reworked distal ash deposits associated with the  
664 Tungurahua volcano eruptions from the last millennium (Le Pennec et al., 2008). This  
665 deposit originated from small size (1-2 m) landslides affecting the andosol on the upper  
666 Carihuairazo flanks as a result of a large earthquake that affected the Ecuadorian Andes  
667 on June 20<sup>th</sup> 1698 (MSK intensity X,  $M_I$  of 7.3; Beauval et al., 2010; Wolf, 1904). The  
668 landslide's scars are still visible in the topography in the upper flanks of Carihuairazo  
669 (black dotted line, Fig. 2d). Based on detailed field mapping (Vásconez et al., 2009) and  
670 modelling (Vasconez et al., 2019), these authors estimated a total volume of  $80-90 \times 10^6$   
671  $m^3$  for these deposits, as well as a total thickness of up to 40 m from the valley bottom  
672 at the Rio Ambato. These mudflows destroyed the former Ambato town (Wolf, 1904;  
673 Vásconez et al., 2009).

674

## 675 **5. Geochemical characteristics as a tool for discriminating the origin of the** 676 **Ambato basin tephra fallout deposits**

677 Carihuairazo samples define an andesitic to dacitic, medium-K calc-alkaline  
678 trend (Fig. 11) ranging from 59 to 66 wt.%  $SiO_2$ , with very few samples falling in the  
679 field of basaltic andesites (55-56 wt.%  $SiO_2$ ). No significant chemical and mineralogical  
680 differences have been observed between the different volcanic units of Carihuairazo.  
681 We note that distal Ambato basin deposits (*i.e.*, debris avalanche and block-and-ash-  
682 flow deposits) display the same geochemical compositions as the proximal lava flows

683 and domes. In addition, the mineral assemblage of the proximal and distal units remains  
684 unchanged during magmatic differentiation, with a mineral assemblage of plagioclase,  
685 ortho- and clino-pyroxene, amphibole, and Fe-Ti oxides.

686 In contrast, the Ambato basin tephra fallout deposits (red triangles, Fig. 11)  
687 display high-silica dacitic to rhyolitic compositions (from 68 to 79 wt.% SiO<sub>2</sub>) that  
688 clearly define a magmatic trend different than the Carihuairazo one, characterized by  
689 higher K<sub>2</sub>O and other incompatible elements (such as Rb, Ba, La, Nb, Th; Fig. 11). It is  
690 also interesting to note that the silica contents decrease from TFD-1 to TFD-3/4. We  
691 also note that these dacitic to rhyolitic compositions lie along the prolongation of the  
692 Huisla-Mulmul magmatic trend (yellow triangles, Fig. 11). This information, together  
693 with the isopach distribution described previously, argue in favour of the hypothesis  
694 that the source of these Plinian events is the Huisla-Mulmul volcanic complex.

695 In contrast, identifying the source for the younger andesitic tephra samples (A-  
696 TFD) is a challenging task. In Fig. 12, we compare the A-TFD samples with those of  
697 Chimborazo volcano (Samaniego et al., 2012), including the variation fields for the  
698 volcanic products of the volcanoes around the Ambato basin (*i.e.*, Carihuairazo,  
699 Puñalica, and Huisla-Mulmul). This comparison highlights that the A-TFD display a  
700 rather large geochemical variability similar to that observed for the Chimborazo tephra  
701 samples. This supports the hypothesis that the A-TFD are originated from the  
702 Chimborazo volcano.

703 Finally, we also note that Puñalica samples (black stars, Fig. 11) define a  
704 homogenous group of magnesium-rich basaltic andesites and andesites (54-60 wt.%  
705 SiO<sub>2</sub>), with a mineral assemblage composed by plagioclase, ortho- and clino-pyroxene,  
706 olivine and Fe-Ti oxides. We stress that olivine is frequent in these lavas, whereas  
707 amphibole is absent. When considering at some major elements Harker diagrams (for  
708 instance K<sub>2</sub>O and MgO vs. SiO<sub>2</sub>, Fig. 11), Puñalica samples seem to define a single  
709 magmatic trend with Carihuairazo. However, some trace elements concentrations (*e.g.*,  
710 La, Th) and ratios (*e.g.* Th/La) clearly point to a more complex scenario. This  
711 observation argues against a single magmatic system feeding both Carihuairazo and  
712 Puñalica volcanoes. Contrasted ages of Carihuairazo (Middle Pleistocene, 220-150 ka)  
713 and Puñalica (< 18 ka) volcanoes also support this assumption.

714

715 **Figure 12.** Comparison between the regional andesitic tephtras (A-TFD) and the Chimborazo tephtras  
716 (white dots and thin black line field, Samaniego et al., 2012). We also show the variation fields for

717 Carihuaizaro (this work), Puñalica (Narváez et al., 2018) and Huisla-Mulmul (both proximal lavas and  
718 tephra, Ancellin et al., 2017) volcanoes.  
719

## 720 **6. Discussion**

### 721 **6.1. The evolution of Carihuaizaro volcano with recurrent sector collapses**

722 The oldest volcanic units identified in the region correspond to two domes  
723 located to the south of the Rio Ambato valley (*cf.* Sunatza and Cruz Maqui domes),  
724 dated by Bablon et al. (2019) at  $512 \pm 9$  ka (Fig. 13b). This age is almost  
725 contemporaneous to those obtained for Huisla volcano (490-620 ka; Bablon et al., 2019)  
726 and corresponds to the oldest Carihuaizaro volcanic unit. The main volcanic succession  
727 of the Carihuaizaro cone itself correspond to thick lava flows that form its outer western  
728 and southern flanks. Lava flows samples from the lower flanks yield ages in the range  
729 of 200-230 ka (Samaniego et al., 2012). This Basal lava flow succession represents the  
730 main cone-building stage of Carihuaizaro (Fig. 13c), responsible of the construction of  
731 an old edifice that was affected by the successive sector collapses. This edifice was  
732 capped by a summit dome complex, whose remnants were not identified, but produced  
733 the Chibuleo block-and-ash-flow deposits cropping out in the northern lower flank (Fig.  
734 13d). This block-and-ash-flow succession indicates of a large dome-forming phase at  
735 Carihuaizaro. We were unable to date this volcanic succession, however, given that it is  
736 covered by the TFD-1 deposit, we consider that it predates the recurrent volcanic sector  
737 collapses and the block-and-ash-flow deposits that affected Carihuaizaro later.

738 The old Carihuaizaro edifice suffered a large sector collapse that formed some  
739 “torevas” in the proximal north-western part of the avalanche scar, and whose remnants  
740 correspond to the Milincocha hills. This sector collapse triggered a large debris  
741 avalanche deposit (DAD-1, Fig. 13d) that reached the Ambato basin 20-25 km from the  
742 current Carihuaizaro summit. This debris avalanche deposit overlies the Chalupas  
743 ignimbrite and the older Ambato basin deposits. The DAD-1 is covered by the  
744 conspicuous TFD-1. Based on isopach maps and geochemical arguments, this tephra  
745 deposit comes from the nearby Huisla-Mulmul volcanic complex, whose younger lavas  
746 (from Mulmul edifice) were dated at 140-175 ka by Bablon et al. (2019). After the  
747 DAD-1 sector collapse, Carihuaizaro initiated a reconstruction period characterized by  
748 the extrusion of lava domes responsible for the succession of block-and-ash-flows  
749 deposits (L-BAFD). Based on the K-Ar ages of the underlying Chalupas ignimbrite  
750 ( $216 \pm 5$  ka; Bablon et al., 2020), and the overlaying L-BAFD ( $206 \pm 4$  ka), the age of  
751 the DAD-1 is well constrained between these two ages. Following this phase of dome

752 growth and collapse, Carihuairazo reconstructed around 200-185 ka, forming the  
753 Intermediate lava flow succession of the north-eastern and the upper western flanks of  
754 the volcano (Fig. 13e). This period was also characterised by dome growth and collapse  
755 (U-BAFD) and ended with a smaller debris avalanche deposit (DAD-2; Fig. 13e). We  
756 argue that this succession of events succeeded in a relatively short time scale due to the  
757 lack of erosional discordances throughout most of the Ambato basin stratigraphic  
758 succession (Fig. 6).

759

760 **Figure 13.** Synthesis cartoons of the eruptive history of the Ambato Basin since 800 ka. Note that the  
761 morphology of the landscape before the construction of volcanoes (basement in grey and ~500 ka old  
762 domes in green) are speculative and deduced from the present elevation of the basement around them.  
763 Same legend as in Fig. 3.

764

765 The upper part of the Carihuairazo cone was constructed around 150-175 ka,  
766 when it reached its maximum height, about 4800-5000 m asl. The remnants of this  
767 eruptive stage form the Terminal lava succession (Fig. 13f), as well as a few lava domes  
768 that crop out along the Pachanlica valley (Santa Rosa, Cahuito, and Pitiunga domes,  
769 Fig. 3). As no ages younger than  $157 \pm 5$  ka have been obtained from this volcano, we  
770 suggest that Carihuairazo experienced a recurrent sequence of sector collapses and  
771 dome growth/collapse events (DAD-1, L-BAFD, DAD-2, and U-BAFD) during about  
772 50 kyr. Thus, the Carihuairazo evolution roughly lasted between 230 and 150 ka.

773 The upper part of the U-BAFD unit appears as a soil-like, dark horizon,  
774 suggesting a repose time of the deposition process. This disconformity is in agreement  
775 with two radiocarbon ages ( $39.0 \pm 0.4$  ka;  $>45$  ka) obtained at the base of the overlying  
776 TFD-2, implying that the forthcoming debris avalanche deposit (DAD-3 and -4, Fig.  
777 13g) are younger than 40-50 ka. These ages imply that the sector collapse associated  
778 with the DAD-3 occurred several tens of thousands of years after the last volcanic  
779 activity at Carihuairazo. Then, a younger and smaller sector collapse occurred at  
780 Carihuairazo, whose debris avalanche deposit (DAD-4) was mostly channelized by the  
781 main drainages of the Ambato basin (Fig. 13g). Based on stratigraphic information, this  
782 sector collapse probably occurred during or just after the LGM period (*i.e.*, younger  
783 than 20-30 ka). Following this debris avalanche deposit (DAD-4), the only volcanic  
784 products deposited on the Ambato basin correspond to regional andesitic tephra fallout  
785 deposits that were interpreted to originate from the Chimborazo volcano (Samaniego et  
786 al., 2012). The youngest volcanic events that affected this region of the Inter Andean



787 valley correspond to the Puñalica volcano growth (Fig. 13h), that included a succession  
788 of effusive eruptions responsible for a large lava field that was dated at  $18 \pm 3$  ka  
789 (Bablon et al., 2019), as well as explosive deposits associated with the upper Puñalica  
790 pyroclastic cone formation. The structural evolution of Puñalica, as well as the detailed  
791 description of its eruptive dynamisms and petrology is beyond the scope of this study  
792 and it will be detailed in a forthcoming manuscript. Lastly, during historical times (1698  
793 *CE*), Carihuairazo flanks were affected by widespread landslides triggered by a large  
794 regional earthquake, these landslides evolved to large debris flows that flowed by the  
795 main drainages.

796

## 797 **6.2. Successive destabilization of a summit dome complex**

798 In Ecuador, debris avalanche deposits formed as a result of sector collapses have  
799 been described at Chimborazo (Bernard et al., 2008; Samaniego et al., 2012);  
800 Tungurahua (Hall et al., 1999; Bablon et al., 2018); Cotopaxi (Hall and Mothes, 2008;  
801 Vezzoli et al., 2017); Imbabura (Le Pennec et al., 2011; Andrade et al., 2019); Cubilche  
802 (Roverato et al., 2018; Navarrete et al., 2021); Pichincha (Robin et al., 2010); Mojanda-  
803 Fuya Fuya (Robin et al., 2009); Huisla-Mulmul (Espín et al., 2019); and Sangay  
804 (Monzier et al., 1999; Valverde et al., 2021). The Carihuairazo evolution is a unique  
805 case-study in the Ecuadorian context because it experienced at least four sector  
806 collapses (and the subsequent debris avalanche deposits, DAD-1 to -4) during its life-  
807 time. The first two debris avalanche deposits (DAD-1 and -2), were followed by dome  
808 collapse block-and-ash flow deposits (L- and U-BAFD). This stratigraphic evidence  
809 implies that following the large DAD-1 event, Carihuairazo started a  
810 construction/destruction period comprised in a relatively short time scale that lasted for  
811 several 10's kyr. In contrast, the two youngest debris avalanches (DAD-3 and -4) were  
812 unrelated to synchronous volcanic activity. They may have been related to hydrothermal  
813 alteration of the edifice, seismic activity, and/or gravitational destabilization related  
814 with its location in the eastern flank of the Western Cordillera. In addition, the profiles  
815 along the thalwegs of the main drainages of the eastern half of the volcano are similar  
816 and not showing a large depression (Fig. 4b-d), suggesting that the successive collapses  
817 should be filled by the avalanche deposits and the subsequent eruptive products, and  
818 may have been eroded by glacier activity. We should also mention that the first three  
819 major DAD occurred before the Last Glacial Maximum, whereas the DAD-4 was a

820 younger and smaller event that did not significantly affect the morphology of the  
821 volcano.

822

### 823 **6.3. Edifice volumes and eruptive rates**

824 Results of the volumes, eruptive and erosion rates are summarized in Table 4.  
825 Eruptive rates should be considered with caution. Indeed, they can be underestimated  
826 due to the pyroclastic material missing in the volume calculation and a biased elevation  
827 model of the basement beneath the volcano; or overestimated due to an incomplete  
828 sampling leading to an erroneous determination of the construction period. However,  
829 they provide a first-order estimate of the volcanic output rates. Considering that the  
830 construction of the Carihuairazo volcano occurred between  $223 \pm 6$  and  $157 \pm 5$  ka  
831 (Samaniego et al., 2012; Table 2), and that the volume of emitted products reached  $97 \pm$   
832  $53 \text{ km}^3$ , we obtain an eruptive rate of  $1.5 \pm 0.9 \text{ km}^3/\text{kyr}$ . This rate is similar or  
833 somewhat higher to the values estimated for other Ecuadorian volcanoes such as Viejo  
834 Cayambe ( $1.0\text{-}1.5 \text{ km}^3/\text{ka}$ ; Samaniego et al., 2005), Guagua Pichincha ( $0.6\text{-}0.8 \text{ km}^3/\text{ka}$ ;  
835 Robin et al., 2010), Chimborazo ( $0.5\text{-}0.8 \text{ km}^3/\text{ka}$ ; Samaniego et al., 2012), and old  
836 Tungurahua I ( $0.6\text{-}0.8 \text{ km}^3/\text{ka}$ ; Bablon et al., 2018). At the Andean scale, the eruptive  
837 rate estimated for Carihuairazo are higher than that of other well-studied volcanoes such  
838 as El Misti ( $0.63 \text{ km}^3/\text{ka}$ , Thouret et al., 2001) and Puyehue-Cordón Caulle ( $0.40\text{-}0.50$   
839  $\text{km}^3/\text{ka}$ , Singer et al., 2008). The eruptive rate estimated for Carihuairazo is notably  
840 higher than that calculated for most of the large, long-lived Andean volcanoes such as  
841 Aucanquilcha ( $0.05\text{-}0.16 \text{ km}^3/\text{ka}$ , Klemetti and Grunder, 2008); Ampato-Sabancaya  
842 ( $0.10\text{-}0.12 \text{ km}^3/\text{ka}$ , Samaniego et al., 2016), Ubinas ( $0.10\text{-}0.20 \text{ km}^3/\text{ka}$ , Thouret et al.,  
843 2005) and Parinacota ( $0.25\text{-}0.30 \text{ km}^3/\text{ka}$ , Hora et al., 2007). This difference is mostly  
844 due to the fact that Carihuairazo growth is surprisingly short ( $66 \pm 6$  ka), in comparison  
845 with most of the edifices previously mentioned, whose lifespan is much longer (several  
846 hundreds of ka). Indeed, Carihuairazo seems to have grown quite continuously, without  
847 long repose periods, as is common in many arc volcanoes.

848 Finally, considering that the quiescence period of the main edifice of the  
849 Carihuairazo volcano started at  $157 \pm 5$  ka (Table 2), and the eroded volume defined by  
850 the current DEM and the pre-erosion modelled paleo-topography, we obtain a volume  
851 of eroded material of  $18 \pm 5 \text{ km}^3$ . We used erosion rate to extrapolate the volume of  
852 material eroded during its construction (*i.e.*, between 223 and 157 ka), and obtained  $8 \pm$   
853  $2 \text{ km}^3$ . Adding the volume dismantled by sector collapses during the construction stage

854 of Carihuairazo (DAD-1 to -4), we obtain a total volume of  $30 \pm 9 \text{ km}^3$ , corresponding  
855 to an erosion rate of about  $0.1 \text{ km}^3/\text{ka}$ . This latter is similar to the erosion rate obtained  
856 for Ecuadorian volcanoes located in the Cordilleras, and higher than those obtained for  
857 volcanoes located within the Inter Andean Valley (Bablon et al., 2020), which are less  
858 affected by orographic rainfalls and glacial erosion.

859

#### 860 **6.4. The Carihuairazo evolution and the link with the nearby Chimborazo**

861 In his pioneering work on glacial and volcanic geomorphology, Clapperton  
862 (1990) described Chimborazo and Carihuairazo volcanoes as being part of a same  
863 volcanic massif. Indeed, both edifices are just 10 km apart and are located on a NE-SW  
864 trend roughly parallel to the large crustal tectonic structure named the Chingual-  
865 Cosanga-Pallatanga-Puna fault system (CCPP, Baize et al., 2020). In addition, both  
866 volcanic systems share a similar geochemical signature (Samaniego et al., 2012;  
867 Ancellin et al., 2017). However, the structural development of each volcano is  
868 independent and a temporal gap between Carihuairazo and Chimborazo was suggested  
869 by Samaniego et al. (2012). This interpretation is based on field observation at the  
870 Abraspungo valley, where the older lavas of Carihuairazo (Piedra Negra succession)  
871 underlie the older lavas of Chimborazo (Abraspungo lava succession, Samaniego et al.,  
872 2012). The new chronological data presented here confirms this hypothesis because  
873 Carihuairazo development is constrained between 230 and 150 ka, whereas Chimborazo  
874 lifetime is younger than 100-120 ka.

875

#### 876 **7. Conclusions**

877 Carihuairazo is a mostly andesitic stratovolcano that overlooks the Ambato  
878 basin, a tectonic depression located at the southern termination of the Ecuadorian arc.  
879 The basal edifice is mainly composed of an andesitic lava flow succession dated at 230-  
880 200 ka, followed by an intermediate lava flow succession (200-185 ka) and a terminal  
881 lava flow succession (175-150 ka) that included a summit dome complex. This edifice  
882 suffered a first sector collapse that was responsible for a large debris avalanche deposit  
883 (DAD-1) that covers the entire Ambato basin. This event occurred between  $206 \pm 4$  and  
884  $216 \pm 5$  ka. Then, Carihuairazo started a succession of construction (Intermediate and  
885 Terminal lava flow successions) and destruction (L-BAFD, DAD-2, U-BAFD) stages  
886 lasting about 50 ky (*i.e.*, from 200 to 150 ka). This volcanic succession is recorded in  
887 the Ambato basin, interlayered with several tephra fallout deposits (TFD-1 to -4) whose

888 source is the nearby Huisla-Mulmul volcanic complex. The current morphology of  
889 Carihuairazo results from two additional sector collapses (DAD-3 and -4) that occurred  
890 during the past 40-50 ka, *i.e.*, following a long period (at least 100 ka) without volcanic  
891 activity. The evolution of the Carihuairazo edifice, recorded in the medial-distal  
892 deposits of the Ambato basin, represents a unique example in the Ecuadorian arc of an  
893 edifice that experienced recurrent sector collapses during a major part of its volcanic  
894 history.

895

## 896 **Acknowledgments**

897 This work is part of an Ecuadorian-French cooperation programme carried out between  
898 the Instituto Geofísico, Escuela Politécnica Nacional (IG-EPN) and the Institut de  
899 Recherche pour le Développement (IRD, France) through a “Laboratoire Mixte  
900 International” program entitled “Séismes et Volcans dans les Andes du Nord”. We  
901 thank Bastien Eschbach for his help during preparations and K-Ar measurements of  
902 some samples. This research was partially financed by the French Government  
903 Laboratory of Excellence initiative n° ANR-10-LABX-0006, the Région Auvergne and  
904 the European Regional Development Fund. This is Laboratory of Excellence ClerVolc  
905 contribution number XXX.

906

## 907 **References**

- 908 Ancellin, M.A., Samaniego, P., Vlastélic, I., Nauret, F., Gannoun, A., Hidalgo, S., 2017.  
909 Across-arc versus along-arc Sr-Nd-Pb isotope variations in the Ecuadorian volcanic  
910 arc. *Geochem. Geophys. Geosyst.* 18, 1163-1188.
- 911 Andrade, S.D., van Wyk de Vries, B., Robin, C., 2019. Imbabura volcano (Ecuador):  
912 the influence of dipping-substrata on the structural development of composite  
913 volcanoes during strike-slip faulting. *J. Volcanol. Geotherm. Res.* 385, 68–80.
- 914 Araujo, S., Valette, B., Potin, B., Ruiz, M., 2021. A preliminary seismic travel time  
915 tomography beneath Ecuador from data of the national network. *J. S. Am. Earth Sci.*  
916 111, 103486.
- 917 Aspden, J.A., Litherland, M., 1992. The geology and Mesozoic collisional history of the  
918 Cordillera Real, Ecuador. *Tectonophysics* 205, 187–204.
- 919 Bablon, M., Quidelleur, X., Samaniego, P., Le Pennec, J.L., Lahitte, P., Liorzou, C.,  
920 Bustillos, J.E., Hidalgo, S., 2018. Eruptive chronology of Tungurahua volcano

921 (Ecuador) revisited based on new K-Ar ages and geomorphological reconstructions.  
922 J. Volcanol. Geotherm. Res. 357, 378–398.

923 Bablon, M., Quidelleur, X., Samaniego, P., Le Pennec, J.L., Audin, L., Jomard, H.,  
924 Baize, S., Liorzou, C., Hidalgo, S., Alvarado, A., 2019. Interactions between  
925 volcanism and geodynamics in the southern termination of the Ecuadorian arc.  
926 Tectonophysics 751, 54-72.

927 Bablon, M., Quidelleur, X., Siani, G., Samaniego, P., Le Pennec, J.L., Nouet, J.,  
928 Liorzou, C., Santamaría, S., Hidalgo, S., 2020. Glass shard K-Ar dating of the  
929 Chalupas caldera major eruption: Main Pleistocene stratigraphic marker of the  
930 Ecuadorian volcanic arc. Quaternary Geochronology 57, 101053.

931 Baize, S., Audin, L., Alvarado, A., Jomard, H., Bablon, M., Champenois, J., Espin, P.,  
932 Samaniego, P., Quidelleur, X., Le Pennec, J.L., 2020. Active tectonics and  
933 earthquake geology along the Pallatanga fault, Central Andes of Ecuador. Frontiers  
934 in Earth Science 8, 193.

935 Beate, B., Hammersley, L., DePaolo, D., Deino, A.I., 2006. La Edad de la Ignimbrita de  
936 Chalupas, prov. de Cotopaxi, Ecuador, y su importancia como marcador  
937 estratigráfico. 6th Jornadas en Ciencias de la Tierra (EPN, Quito), pp. 68–71.

938 Beauval, C., Yepes, H., Bakun, W.H., Egred, J., Alvarado, A., Singaicho, J.C., 2010.  
939 Locations and magnitudes of historical earthquakes in the Sierra of Ecuador (1587-  
940 1996). Geophysical Journal International 181, 1613–1633.

941 Belousov, A., Belousova, M., Voight, B., 1999. Multiple edifice failures, debris  
942 avalanches and associated eruptions in the Holocene history of Shiveluch volcano,  
943 Kamchatka, Russia. Bull. Volcanol. 61, 324–342.

944 Bernard, B., van Wyk de Vries, B., Barba, B., Robin, C., Leyrit, H., Alcaraz, S.,  
945 Samaniego, P., 2008. The Chimborazo sector collapse and debris avalanche: deposit  
946 characteristics as evidence of emplacement mechanisms. J. Volcanol. Geotherm.  
947 Res. 176, 36-43.

948 Calder, E.S., Lavallée, Y., Kendrick, J.E., Bernstein, M., 2015. Lava dome eruptions.  
949 The Encyclopedia of Volcanoes, 2nd ed.; Sigurdsson, H., Houghton, B., McNutt, S.,  
950 Rymer, H., Stix, J., Eds, 343-362.

951 Cassignol, C., Gillot, P.Y., 1982. Range and effectiveness of unspiked potassium-argon  
952 dating: experimental groundwork and applications, in: Odin, G.S. (Ed.), Numerical  
953 Dating in Stratigraphy. John Wiley & Sons, pp. 159–179.

- 954 Clapperton, C.M., 1990. Glacial and volcanic geomorphology of the Chimborazo-  
955 Carihuairazo Massif, Ecuadorian Andes. *Trans. R. Soc. Edinb. Earth Sci.* 81, 91–  
956 116.
- 957 Cotten, J., Le Dez, A., Bau, M., Caroff, M., Maury, R.C., Dulski, P., Fourcade, S.,  
958 Bohn, M., Brousse, R., 1995. Origin of anomalous rare-earth element and Yttrium  
959 enrichments in subaerial exposed basalts: evidence from French Polynesia. *Chem.*  
960 *Geol.* 119, 115–138.
- 961 Dibacto, S., Lahitte, P., Karátson, D., Hencz, M., Szakács, A., Biró, T., Kovács, I.,  
962 Veres, D., 2020. Growth and erosion rates of the East Carpathians volcanoes  
963 constrained by numerical models: Tectonic and climatic implications.  
964 *Geomorphology* 368, 107352.
- 965 Espín, P., Mothes, P., Hall, M., Valverde, V., Keen, H., 2019. The “Mera” lahar deposit  
966 in the upper Amazon basin: Transformation of a late Pleistocene collapse at Huisla  
967 volcano, Central Ecuador. *J. Volcanol. Geotherm. Res.* 385, 103–119.
- 968 Germa, A., Quidelleur, X., Lahitte, P., Labanieh, S., Chauvel, C., 2011. The K–Ar  
969 Cassagnol–Gillot technique applied to western Martinique lavas: A record of Lesser  
970 Antilles arc activity from 2Ma to Mount Pelée volcanism. *Quaternary*  
971 *Geochronology* 6, 341–355.
- 972 Germa, A., Kimball, S., Martens, A., Quidelleur, X., Bablon, M., 2019. Preservation of  
973 inherited argon in plagioclase crystals and implication for residence time after  
974 reservoir remobilization. In *AGU Fall Meeting Abstracts (Vol. 2019, pp. V51F-*  
975 *0120)*.
- 976 Gillot, P.Y., Hildenbrand, A., Lefèvre, J.C., Albore-Livadie, C., 2006. The K/Ar dating  
977 method: principle, analytical techniques, and application to Holocene volcanic  
978 eruptions in Southern Italy. *Acta Vulcanologica* 18, 55–66.
- 979 Gillot, P.Y., Cornette, Y., Max, N., Floris, B., 1992. Two reference materials, trachytes  
980 MDO- G and ISH-G, for argon dating (K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$ ) of Pleistocene and  
981 Holocene rocks. *Geostand. Newslett.* 16, 55–60.
- 982 Glicken, H., 1991. Sedimentary architecture of large volcanic-debris avalanches.  
983 *Sedimentation in Volcanic Settings, SEPM Spec. Pub.* 45, 99–106.
- 984 Grosse, P., Orihashi, Y., Guzmán, S.R., Sumino, H., Nagao, K., 2018. Eruptive history  
985 of Incahuasi, Falso Azufre and El Cónдор Quaternary composite volcanoes, southern  
986 Central Andes. *Bulletin of Volcanology* 80, 44.

987 Hall, M.L., Robin, C., Beate, B., Mothes, P., Monzier, M., 1999. Tungurahua Volcano,  
988 Ecuador: structure, eruptive history and hazards. *J. Volcanol. Geotherm. Res.* 91, 1–  
989 21.

990 Hall, M.L., Samaniego, P., Le Pennec, J.L., Johnson, J., 2008. Late Pliocene to present  
991 volcanism in the Ecuadorian Andes. *J. Volcanol. Geotherm. Res.* 176, 1-6.

992 Hall, M.L., Mothes, P., 2008. The rhyolitic–andesitic eruptive history of Cotopaxi  
993 volcano, Ecuador. *Bull. Volcanol.* 70, 675–702.

994 Harford, C.L., Pringle, M.S., Sparks, R.S.J., Young, S.R., 2002. The volcanic evolution  
995 of Montserrat using  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology. Geological Society, London,  
996 *Memoirs* 21, 93–113.

997 Harpel, C.J., de Silva, S., Salas, G., 2011. The 2 Ka Eruption of Misti Volcano,  
998 Southern Peru-The Most Recent Plinian Eruption of Arequipa’s Iconic Volcano.  
999 *Geol. Soc. Am. Spec. Pap.* 484, 72.

1000 Hess, J.C., Lippolt, H.J., 1994. Compilation of K-Ar Measurements on HD-B1 Standard  
1001 Bio- tite, 1994 Status Report. *Phaneroz. Time Scale, Bull. Liais. Inform. IUGS*  
1002 *Subcomm. Geochronol.* p. 122.

1003 Hora, J.M., Singer, B.S., Wörner, G., 2007. Volcano evolution and eruptive flux on the  
1004 thick crust of the Andean Central Volcanic Zone:  $^{40}\text{Ar}/^{39}\text{Ar}$  constraints from  
1005 Volcan Parinacota, Chile. *Geol. Soc. Am. Bull.* 119, 343–362.

1006 Hughes, R.A., Pilatasig, L.F., 2002. Cretaceous and tertiary terrane accretion in the  
1007 cordillera Occidental of the Andes of Ecuador. *Tectonophysics* 345, 29–48.

1008 Jaillard, E., Ordóñez, M., Suarez, J., Toro, J., Iza, D., Lugo, W., 2004. Stratigraphy of  
1009 the late Cretaceous–Paleogene deposits of the Cordillera Occidental of central  
1010 Ecuador: geodynamic implications. *J. S. Am. Earth Sci.* 17, 49–58.

1011 Klemetti, E.W., Grunder, A.L., 2008. Volcanic evolution of Volcán Aucanquilcha: a  
1012 long- lived dacite volcano in the Central Andes of northern Chile. *Bull. Volcanol.* 70,  
1013 633–650.

1014 Lahitte, P., Samper, A., Quidelleur, X., 2012. DEM-based reconstruction of southern  
1015 Basse-Terre volcanoes (Guadeloupe archipelago, FWI): Contribution to the Lesser  
1016 Antilles Arc construction rates and magma production. *Geomorphology* 136, 148–  
1017 164.

1018 Lahitte, P., Dibacto, S., Karátson, D., Gertisser, R., Veres, D., 2019. Eruptive history of  
1019 the Late Quaternary Ciomadul (Csomád) volcano, East Carpathians, part I: timing of  
1020 lava dome activity. *Bull. Volcanol.* 81, 27.

- 1021 Lavenu, A., Noblet, C., Bonhomme, M.G., Egüez, A., Dugas, F., Vivier, G., 1992. New  
1022 K-Ar age dates of Neogene and Quaternary volcanic rocks from the Ecuadorian  
1023 Andes: Implications for the relationship between sedimentation, volcanism, and  
1024 tectonics. *J. S. Am. Earth Sci.* 5, 309–320.
- 1025 Le Pennec, J.L., Jaya, D., Samaniego, P., Ramón, P., Moreno Yáñez, S., Egred, J., van  
1026 der Plicht, J., 2008. The AD 1300–1700 eruptive periods at Tungurahua volcano,  
1027 Ecuador, revealed by historical narratives, stratigraphy and radiocarbon dating, *J.*  
1028 *Volcanol. Geotherm. Res.* 176, 70-81.
- 1029 Le Pennec, J.L., Ruiz, A.G., Eissen, J.P., Hall, M.L., Fornari, M., 2011. Identifying  
1030 potentially active volcanoes in the Andes: radiometric evidence for late Pleistocene-  
1031 early Holocene eruptions at Volcán Imbabura, Ecuador. *J. Volcanol. Geotherm. Res.*  
1032 206, 121–135.
- 1033 Marino, J., Samaniego, P., Manrique, N., Valderrama, P., Roche, O., van Wyk de Vries,  
1034 B., Guillou, H., Zerathe, S., Arias, C., Liorzou, C., 2021. The Tutupaca volcanic  
1035 complex (Southern Peru): Eruptive chronology and successive destabilization of a  
1036 dacitic dome complex. *J. S. Am. Earth Sci.* 110, 103227.
- 1037 Monzier, M., Robin, C., Samaniego, P., Hall, M.L., Cotten, J., Mothes, P., Arnaud, N.,  
1038 1999. Sangay volcano, Ecuador: structural development, present activity and  
1039 petrology. *J. Volcanol. Geotherm. Res.* 90, 49-79.
- 1040 Mook, W.G, van der Plicht, J., 1999. Reporting <sup>14</sup>C activities and concentrations.  
1041 *Radiocarbon* 41, 227-239.
- 1042 Narváez, D., Rose-Koga, E., Samaniego, P., Koga, K.T., Hidalgo, S., 2018.  
1043 Constraining magma sources using primitive olivine-hosted melt inclusions from  
1044 Puñalica and Sangay volcanoes (Ecuador). *Contrib. Mineral. Petrol.* 173, 80.
- 1045 Navarrete, W.F., Le Pennec, J.L., Solano, S., Liorzou, C., Ruiz, G.A., 2021. A first  
1046 reconstruction of the evolution of Cubilche Volcanic Complex, Imbabura Province,  
1047 Ecuador. *J. Volcanol. Geotherm. Res.* 406, 107023.
- 1048 Ordóñez, J., 2012. Depósitos volcánicos del Pleistoceno Tardío en la cuenca de  
1049 Ambato: caracterización, distribución y origen. *EPN Memoir*, Quito, pp. 192.
- 1050 Pyle, D., 1989. The thickness, volumen and grainsize of tephra fall deposits. *Bull.*  
1051 *Volcanol.* 55, 523-525.
- 1052 Raczek, I., Stoll, B., Hofmann, A.W., Peter Jochum, K., 2001. High-precision trace  
1053 element data for the USGS reference materials BCR-1, BCR-2, BHVO-1, BHVO-2,



1054 AGV-1, AGV- 2, DTS-1, DTS-2, GSP-1 and GSP-2 by ID-TIMS and MIC-SSMS.  
1055 Geostand. Newslett. 25, 77–86.

1056 Robin, C., Mossand, P., Camus, G., Cantagrel, J.M., Gourgaud, A., Vincent, P.M.,  
1057 1987. Eruptive history of the Colima volcanic complex (Mexico). *J. Volcanol.*  
1058 *Geotherm. Res.* 31, 99-113.

1059 Robin, C., Eissen, J.P., Samaniego, P., Martin, H., Hall, M.L., Cotten, J., 2009.  
1060 Evolution of the late Pleistocene Mojanda Fuya Fuya volcanic complex (Ecuador),  
1061 by progressive adakitic involvement in mantle magma sources. *Bull. Volcanol.* 71,  
1062 233-258.

1063 Robin, C., Samaniego, P., Le Pennec, J.L., Fornari, M., Mothes, P., van der Plicht, J.,  
1064 2010. New radiometric and petrological constraints on the evolution of the Pichincha  
1065 volcanic complex (Ecuador). *Bull. Volcanol.* 72, 1109-1129.

1066 Roverato, M., Larrea, P., Casado, I., Mulas, M., Béjar, G., Bowman, L., 2018.  
1067 Characterization of the Cubilche debris avalanche deposit, a controversial case from  
1068 the northern Andes, Ecuador. *J. Volcanol. Geotherm. Res.* 360, 22–35.

1069 Samaniego, P., Martin, H., Monzier, M., Robin, C., Fornari, M., Eissen, J.P., Cotten, J.,  
1070 2005. Temporal evolution of magmatism at Northern Volcanic Zone of the Andes:  
1071 The geology and petrology of Cayambe volcanic complex (Ecuador). *J. Petrol.* 46,  
1072 2225-2252.

1073 Samaniego, P., Barba, D., Robin, C., Fornari, M., Bernard, B., 2012. Eruptive history of  
1074 Chimborazo volcano (Ecuador): A large, ice-capped and hazardous compound  
1075 volcano of the Northern Andes. *J. Volcanol. Geotherm. Res.* 221-222, 33-51.

1076 Samaniego, P., Valderrama, P., Mariño, J., van Wyk de Vries, B., Roche, O., Manrique,  
1077 N., Chedeville, C., Fidel, L., Malnati, J., 2015. The historical ( $218 \pm 14$  aAP)  
1078 explosive eruption of Tutupaca volcano (Southern Peru). *Bull. Volcanol.* 77, 51.

1079 Samaniego, P., Rivera, M., Mariño, Guillou, H., Liorzou, C., Zerathe, S., Delgado, R.,  
1080 Valderrama, P., Scao, V., 2016. The eruptive chronology of the Ampato-Sabancaya  
1081 volcanic complex (Southern Peru). *J. Volcanol. Geotherm. Res.* 323, 110-128.

1082 Samper, A., Quidelleur, X., Boudon, G., Le Friant, A., Komorowski, J.C., 2008.  
1083 Radiometric dating of three large volume flank collapses in the Lesser Antilles Arc.  
1084 *J. Volcanol. Geotherm. Res.* 176, 485–492.

1085 Santamaria, S., Quidelleur, X., Hidalgo, S., Samaniego, P., Le Pennec, J.L., Liorzou, C.,  
1086 Lahitte, P., Córdova, M., Espín, P., 2022. Geochronological evolution of the

1087 potentially active Iliniza Volcano (Ecuador) based on new K-Ar ages. *J. Volcanol.*  
1088 *Geotherm. Res.* 107489.

1089 Singer, B.S., Jicha, B.R., Harper, M.A., Naranjo, J.A., Lara, L.E., Moreno-Roa, H.,  
1090 2008. Eruptive history, geochronology, and magmatic evolution of the Puyehue-  
1091 Cordón Caulle volcanic complex, Chile. *Geol. Soc. Am. Bull.* 120, 599–618.

1092 Steiger, R.H., Jäger, E., 1977. Subcommittee on geochronology: Convention on the  
1093 use of decay constants in geo- and cosmochronology. *Earth and Planetary Science*  
1094 *Letters* 36, 359–362.

1095 Thouret, J.C., Finizola, A., Fornari, M., Suni, J., Legeley-Padovani, A., Frechen, M.,  
1096 2001. Geology of El Misti volcano nearby the city of Arequipa, Peru. *Geol. Soc. Am.*  
1097 *Bull.* 113, 1593–1610.

1098 Thouret, J.C., Rivera, M., Wörner, G., Gerbe, M.C., Finizola, A., Fornari, M., Gonzales,  
1099 K., 2005. Ubinas: the evolution of the historically most active volcano in southern  
1100 Peru. *Bull. Volcanol.* 67, 557–589.

1101 Valverde, V., Mothes, P.A., Beate, B., Bernard, J., 2021. Enormous and far-reaching  
1102 debris avalanche deposits from Sangay volcano (Ecuador): Multidisciplinary study  
1103 and modelling the 30 ka sector collapse. *J. Volcanol. Geotherm. Res.* 411, 107172.

1104 Van Wyk de Vries, B, Davis, T., 2015. Landslides, debris avalanches and volcanic  
1105 gravitational deformation. *The Encyclopedia of Volcanoes*, 2nd ed.; Sigurdsson, H.,  
1106 Houghton, B., McNutt, S., Rymer, H., Stix, J., Eds, 665-685.

1107 Vásconez, R., Hall, M., Mothes, P., 2009. Devastadores flujos de lodo disparados en el  
1108 volcán Carihuayrazo por el terremoto del 20 de Junio de 1698. *Revista Politécnica:*  
1109 *Monografía de Geología* 7, 30(1), 86-105.

1110 Vascones, F.J., Vásconez, R., Mothes, P., 2019. Flujos de lodo del volcán Carihuairazo  
1111 provocados por el terremoto de Ambato, Ecuador, en 1698 y su reconstrucción  
1112 numérica con perspectivas a futuro. *Revista Geofísica* 69,  
1113 [doi.org/10.35424/rgf.v0i69.937](https://doi.org/10.35424/rgf.v0i69.937)

1114 Vezzoli, L., Apuani, T., Corazzato, C., Uttini, A., 2017. Geological and geotechnical  
1115 characterization of the debris avalanche and pyroclastic deposits of Cotopaxi  
1116 Volcano (Ecuador). A contribute to instability-related hazard studies. *J. Volcanol.*  
1117 *Geotherm. Res.* 332, 51-70.

1118 Wolf, T., 1904. Crónica de los fenómenos volcánicos y terremotos en El Ecuador, con  
1119 algunas noticias sobre otros países de la América Central y Meridional, desde 1533

1120 hasta 1797 (reedited by N. Martínez). Imprenta de la Universidad Central del  
1121 Ecuador, Quito.

1122 Yepes, H., Audin, L., Alvarado, A., Beauval, C., Aguilar, J., Font, Y., Cotton, F., 2016.  
1123 A new view for Ecuador's geodynamics: implication in seismogenic source  
1124 definition and seismic hazard assessment. *Tectonics* 35, 1249-1279.

1125 Zemeny, A., Procter, J., Németh, K., Zellmer, G.F., Zernack, A.V., Cronin, S.J., 2021.  
1126 Elucidating stratovolcano construction from volcanoclastic mass-flow deposits: The  
1127 medial ring-plain of Taranaki Volcano, New Zealand. *Sedimentology* 68, 2422-2449.

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1130 **Table 1.** Selected geochemical analyses for Carihuairazo samples.

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1132 **Table 2.** Unspiked K-Ar ages for Carihuairazo volcano.

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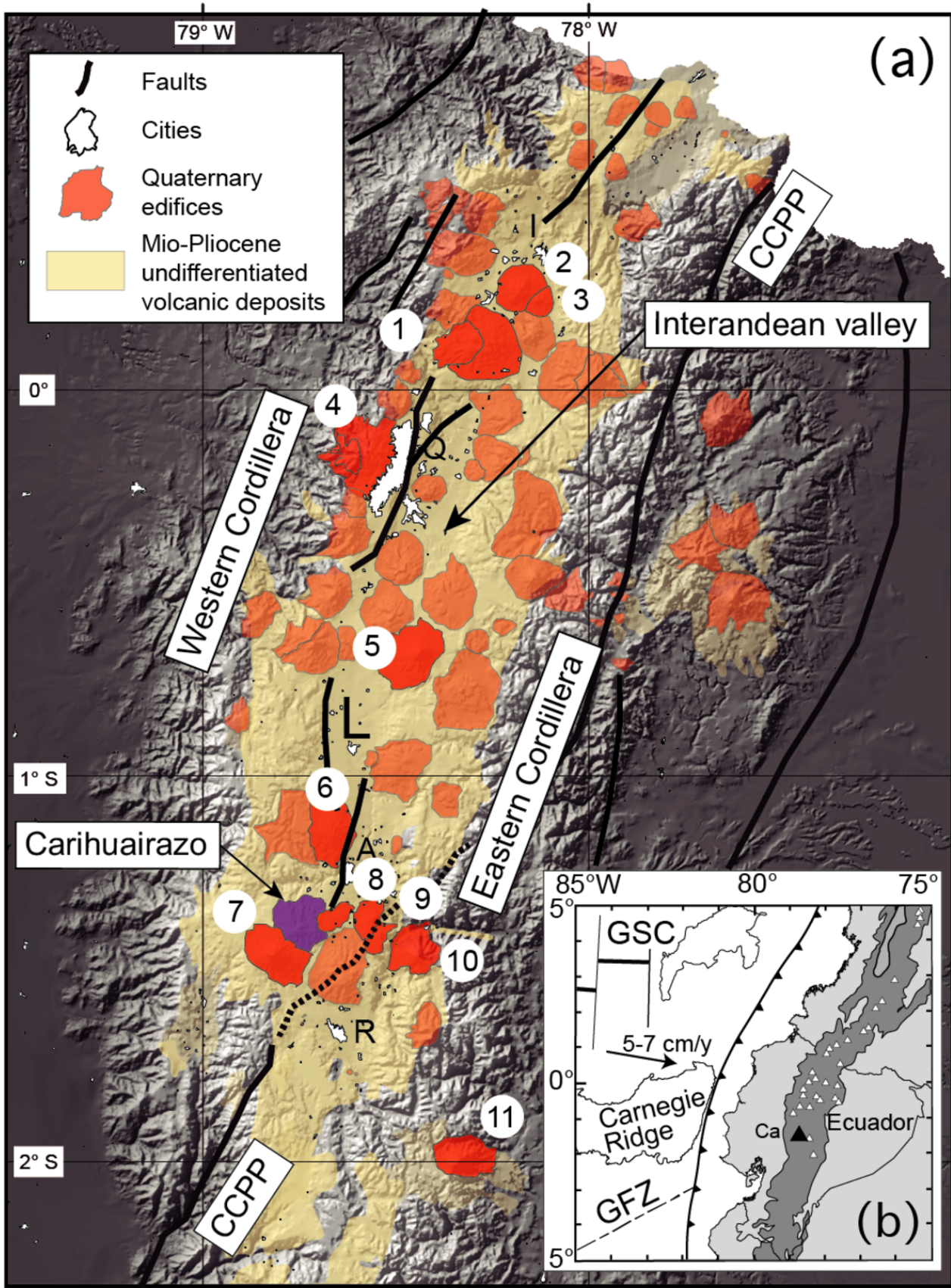
1134 **Table 3.** Radiocarbon ages for the Ambato basin deposits.

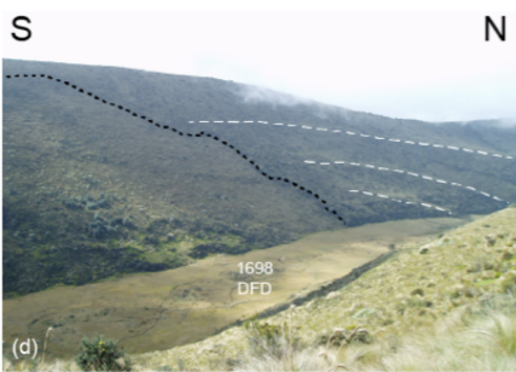
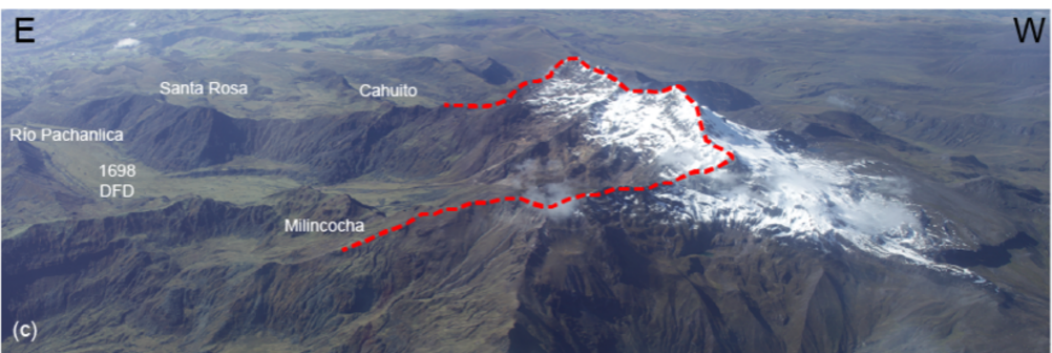
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1136 **Table 4.** Results of volumes, eruptive and erosion rates calculations obtained from the  
1137 numerical paleo-surfaces and given at 1-sigma accuracy. Raw volume corresponds to  
1138 the volume calculated from the surface model without taking into account erosion that  
1139 occurred during the construction. Total volume corresponds to the sum of the raw  
1140 volume, the volume eroded during the construction, calculated based on the erosion rate  
1141 since the end of Carihuairazo construction, and the volume of products mobilized  
1142 during sector collapse events. Volumes of the four DAD calculated using deposit  
1143 thicknesses were converted to a dense rock equivalent (DRE) volume using a debris  
1144 avalanche bulk density of 1950 kg/m<sup>3</sup> (Glicken,1991), and assuming a bulk density of  
1145 2600 kg/m<sup>3</sup> for the entire edifice. \* Samaniego et al. (2012)

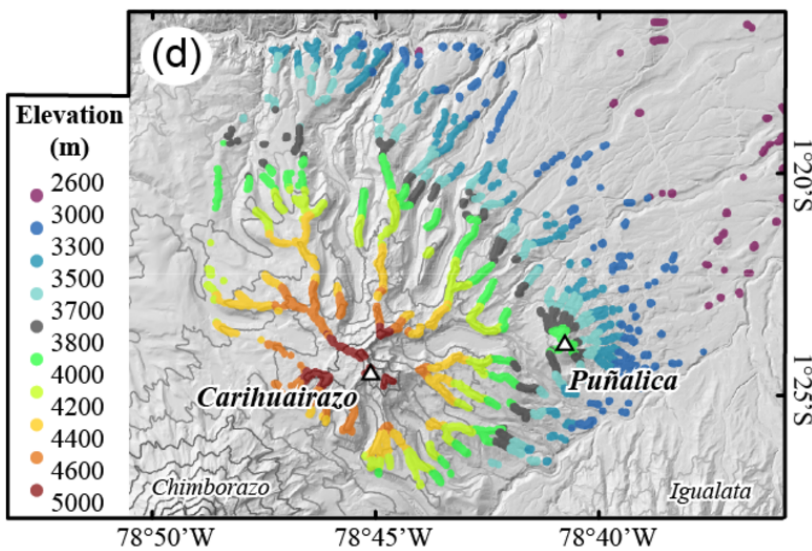
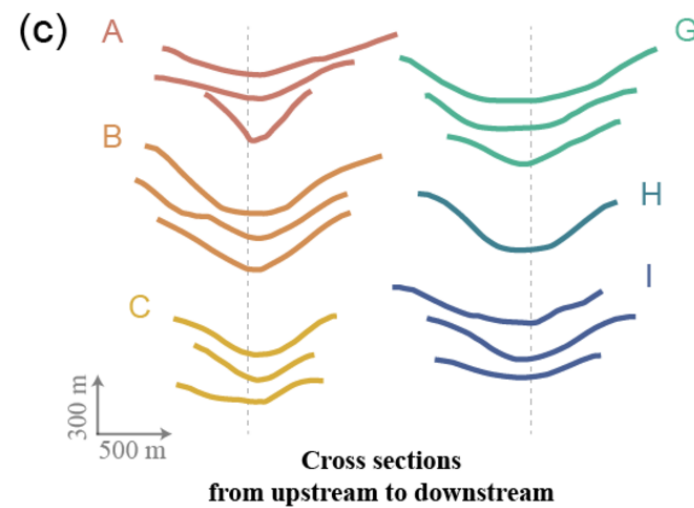
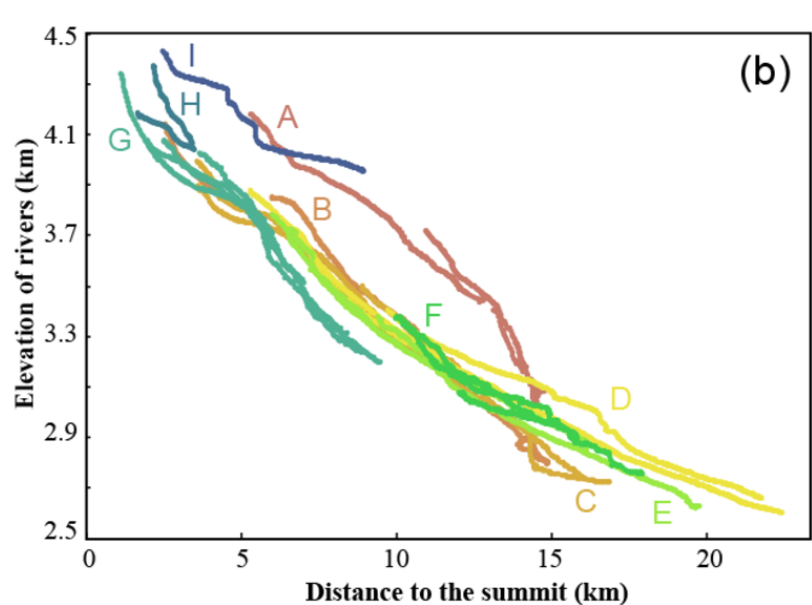
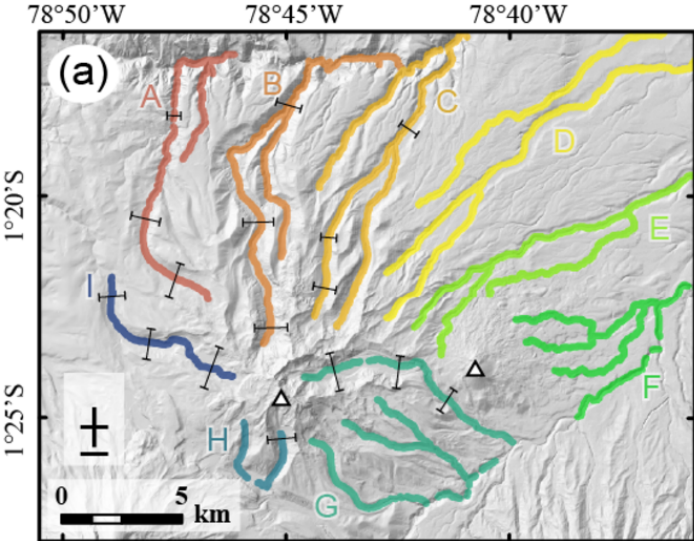
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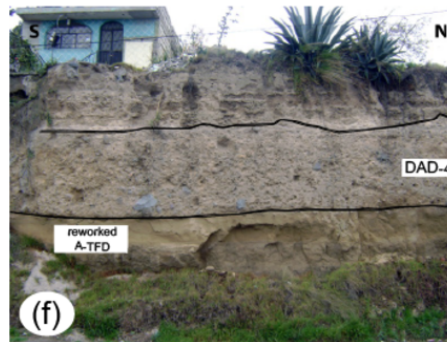
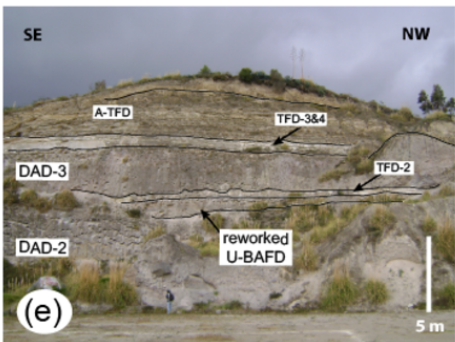
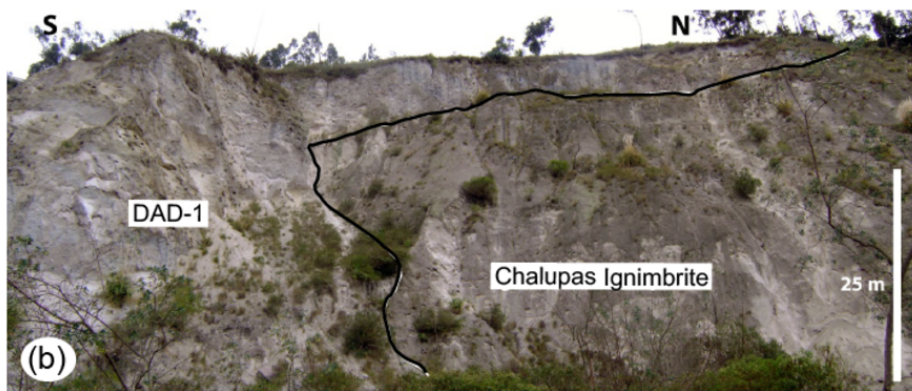
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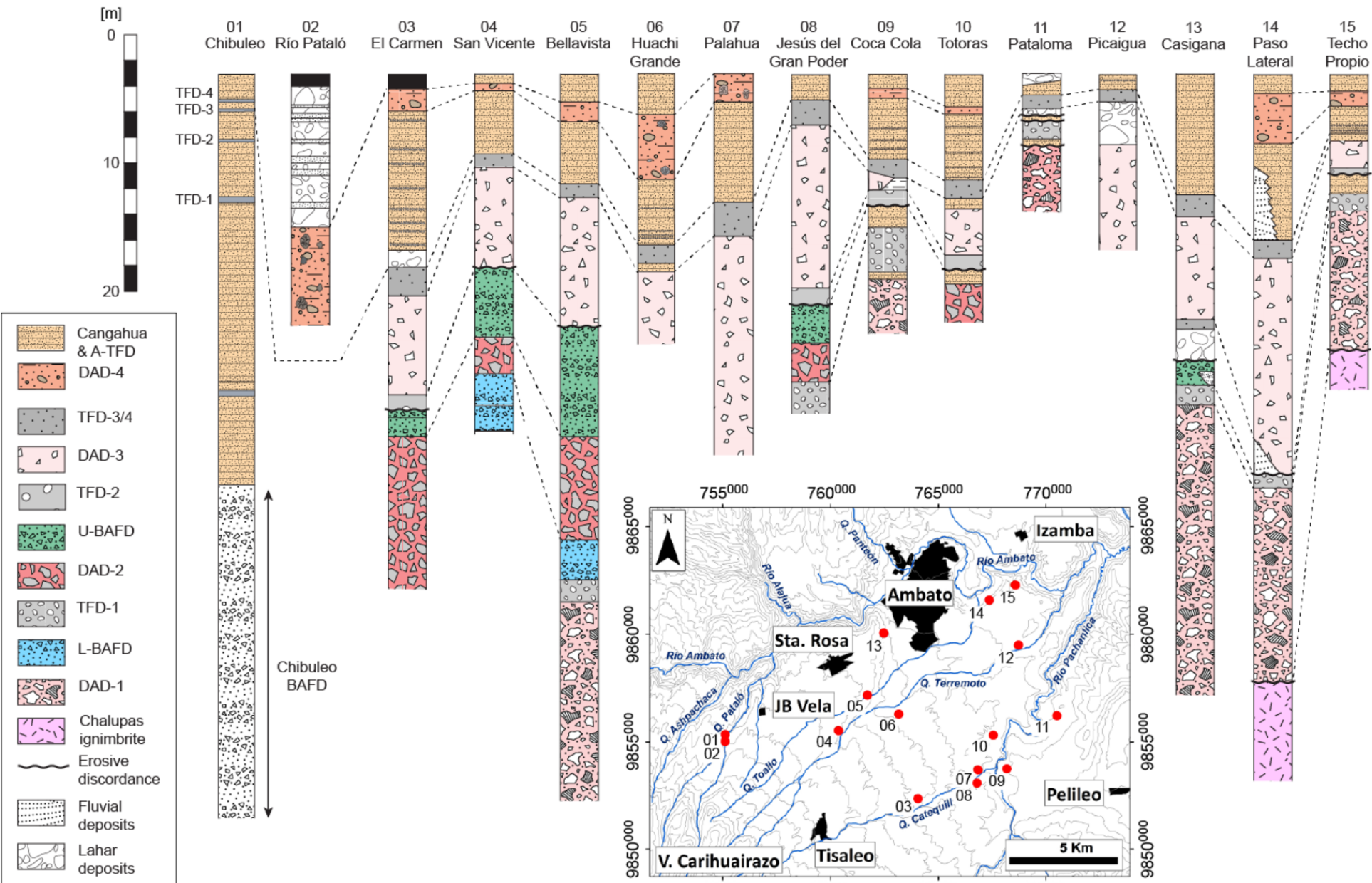


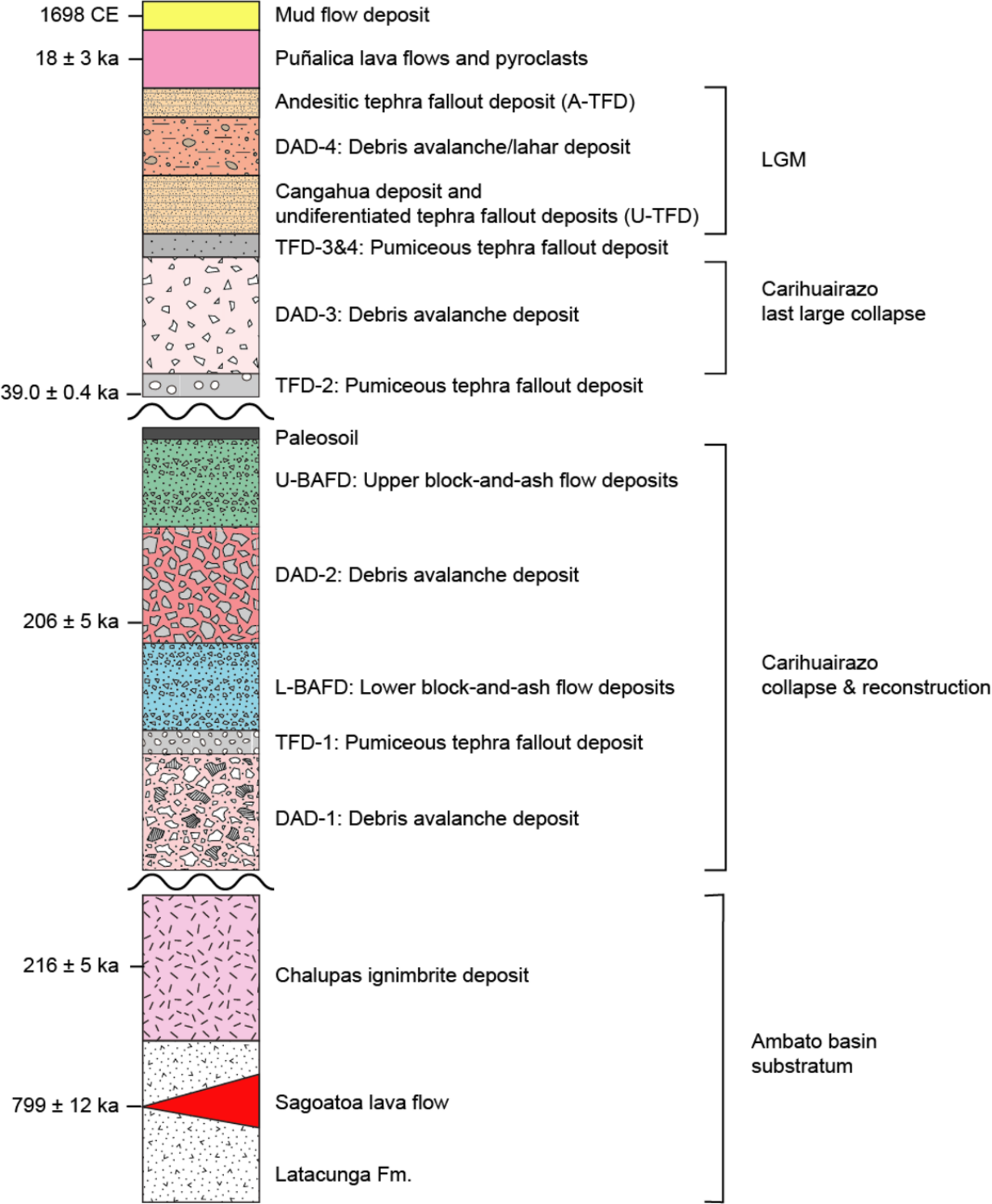


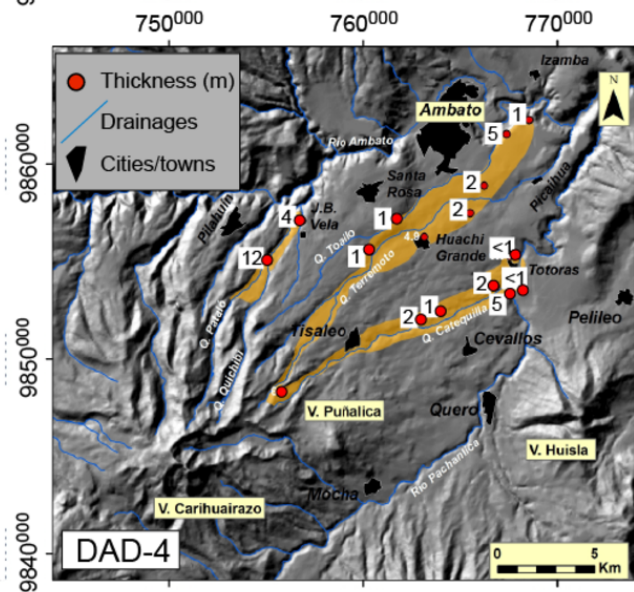
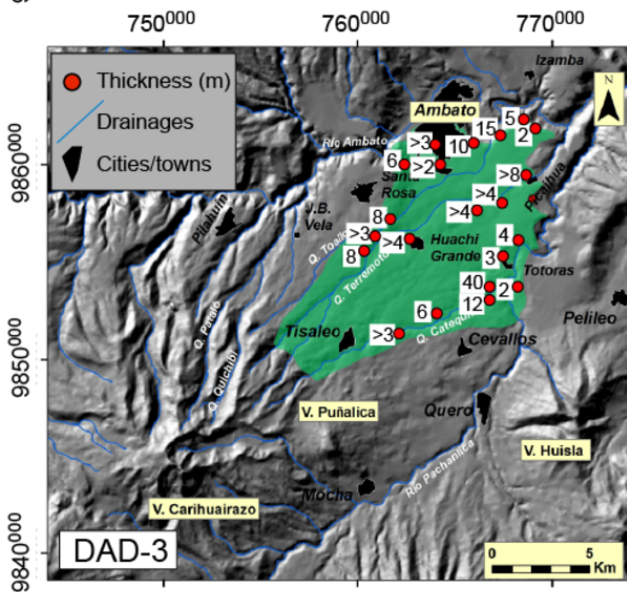
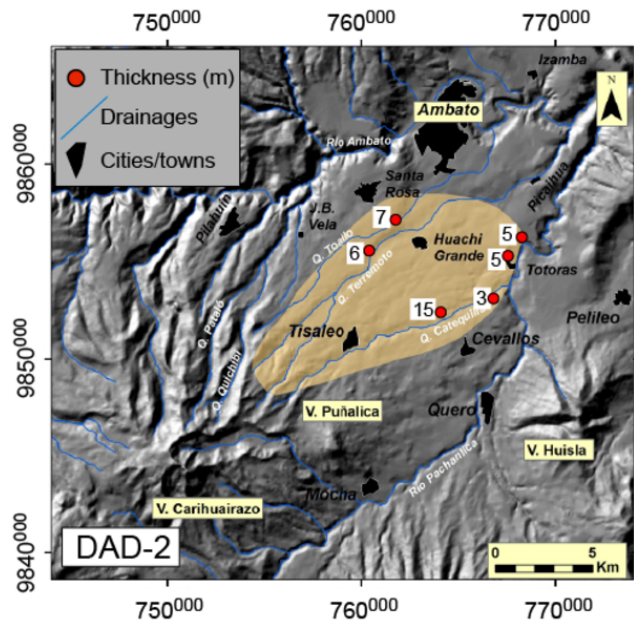
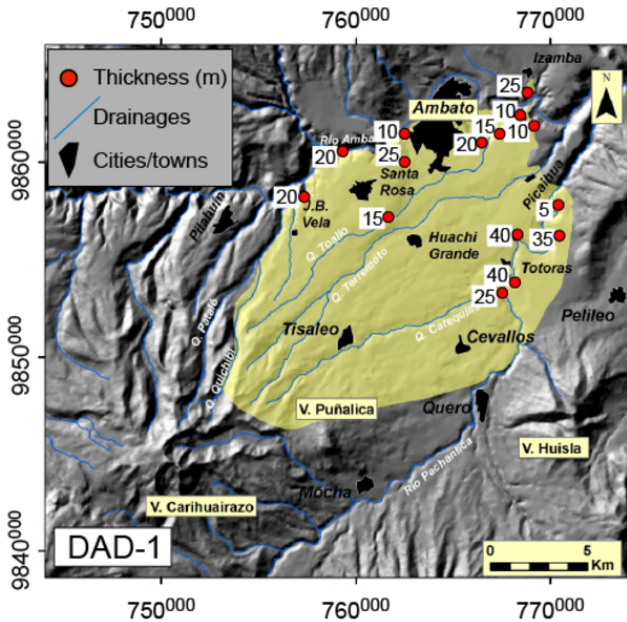


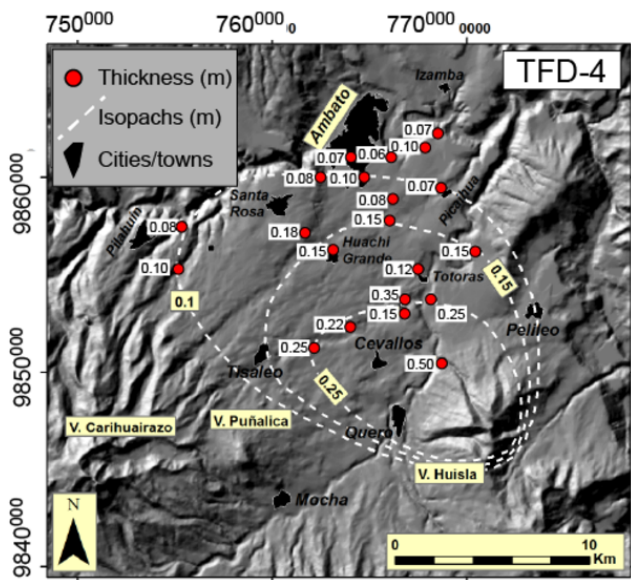
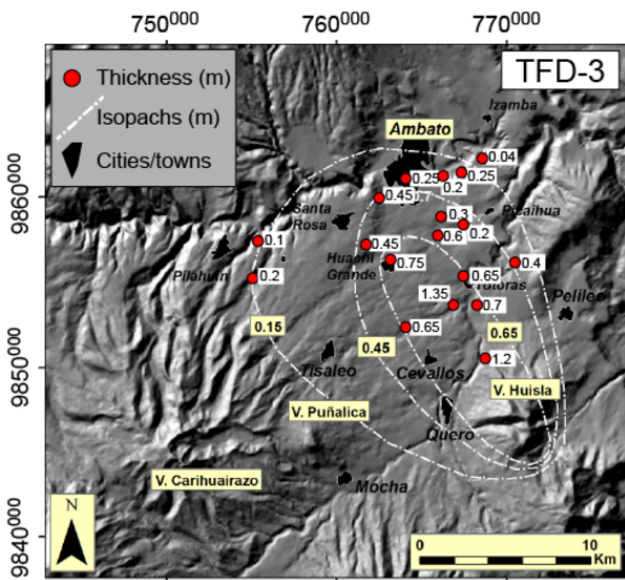
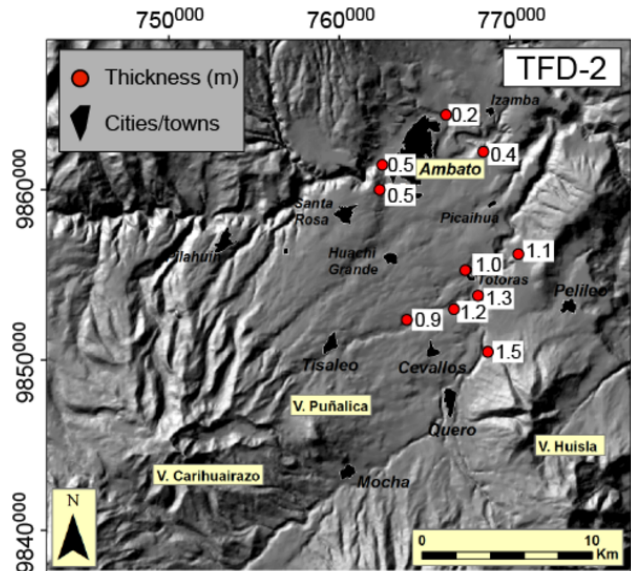
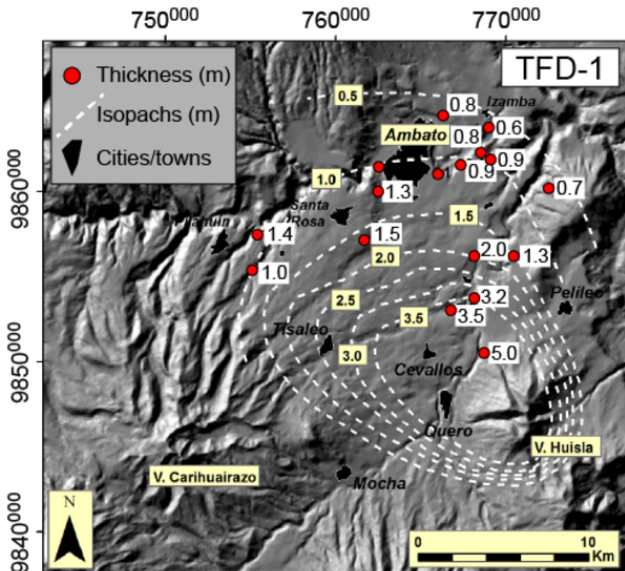


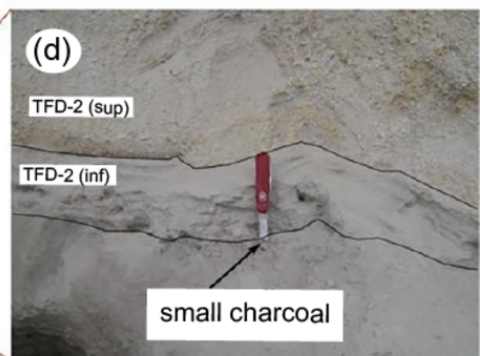
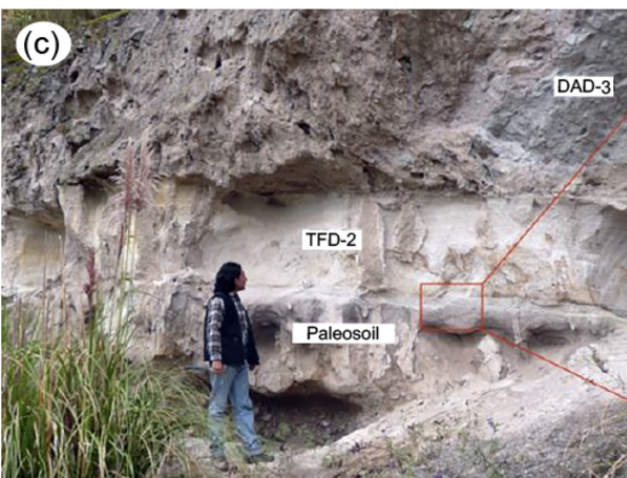
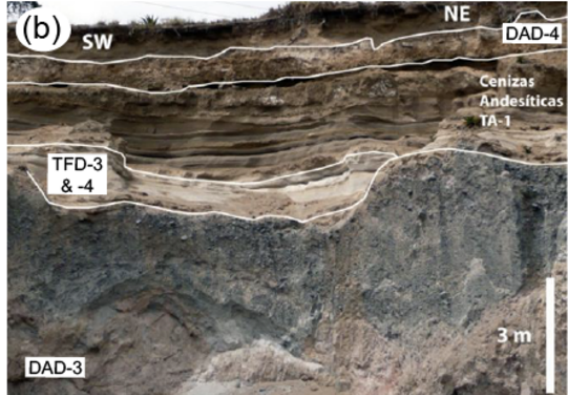
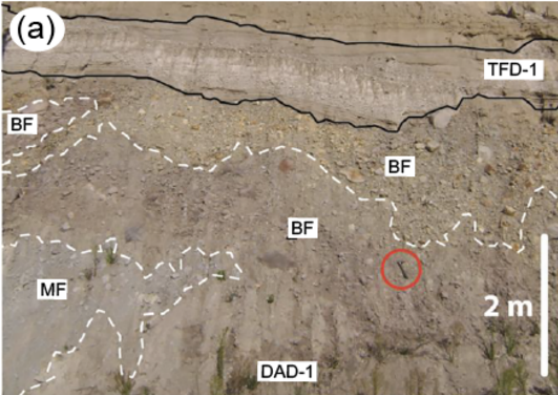


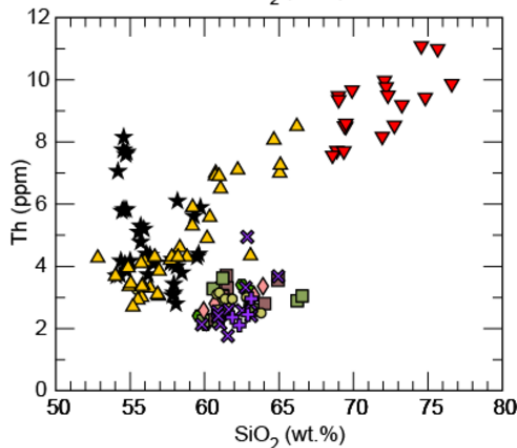
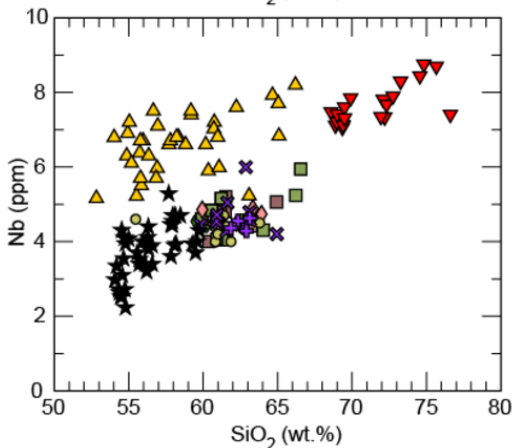
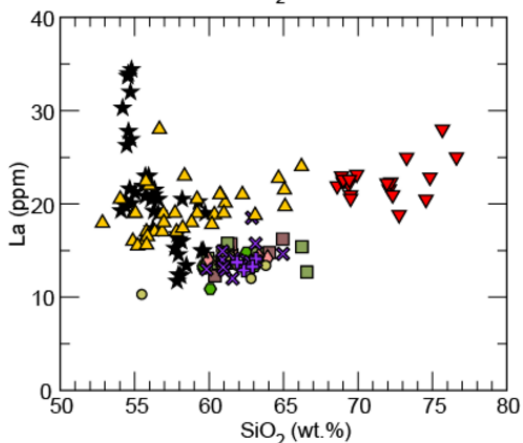
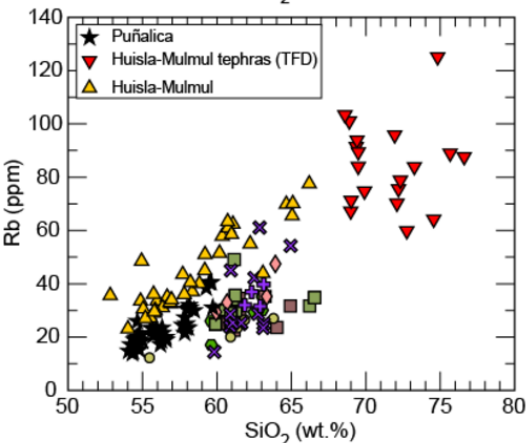
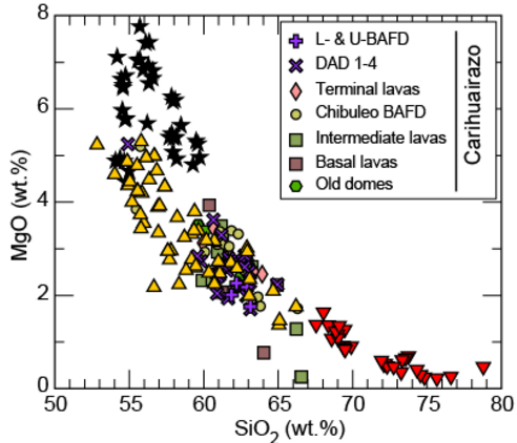
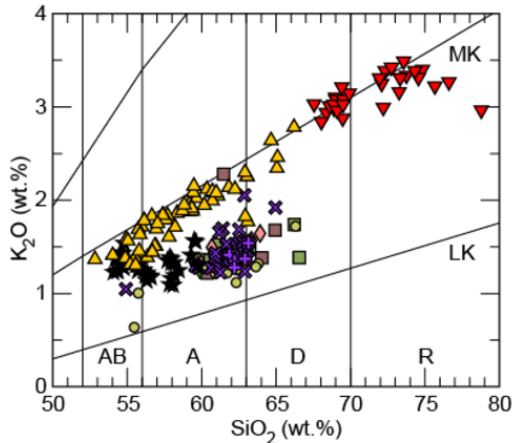


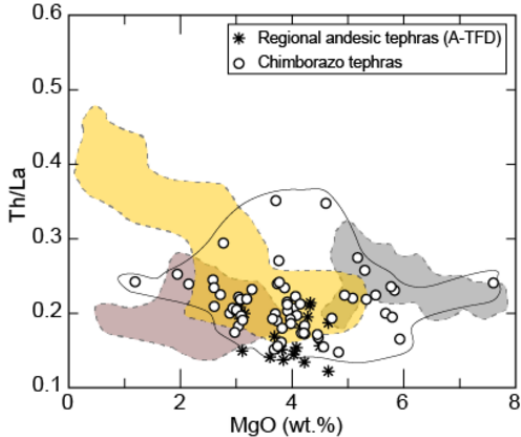
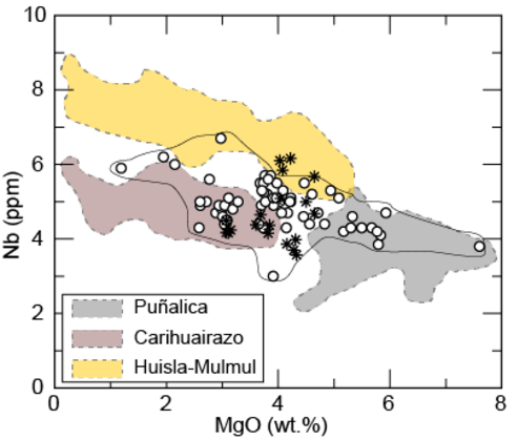


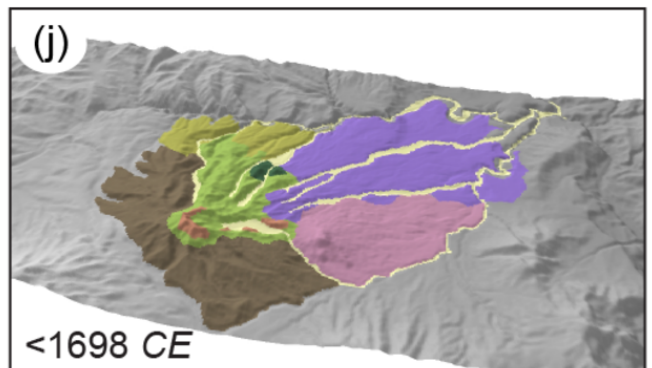
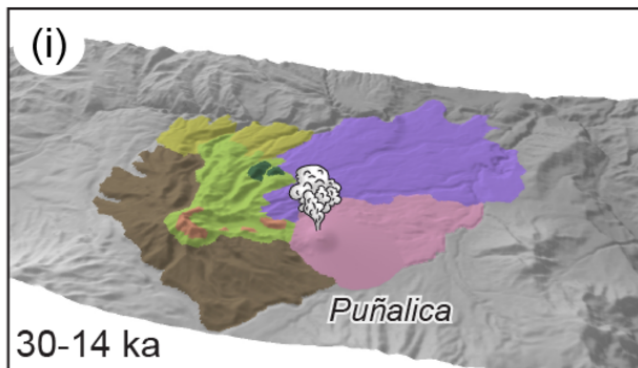
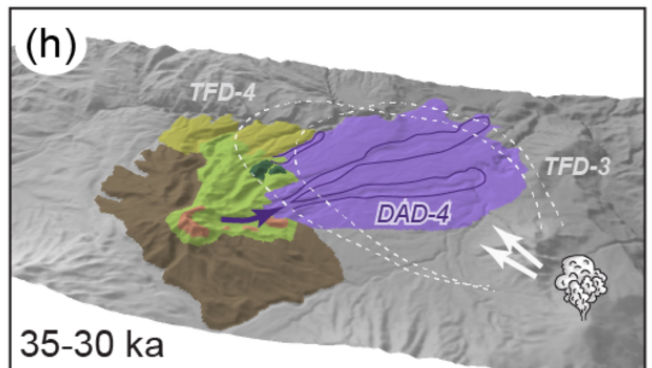
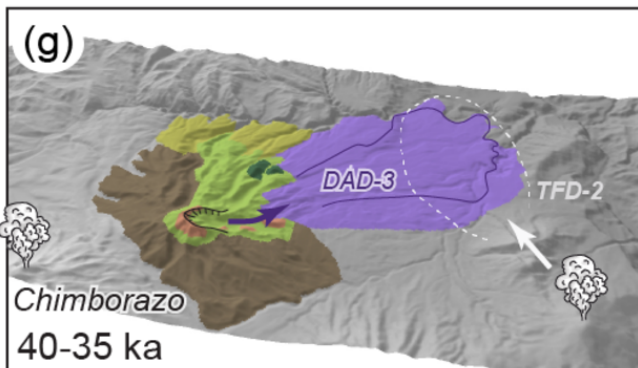
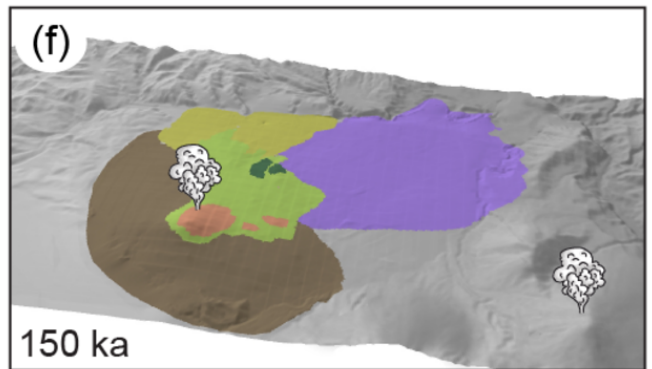
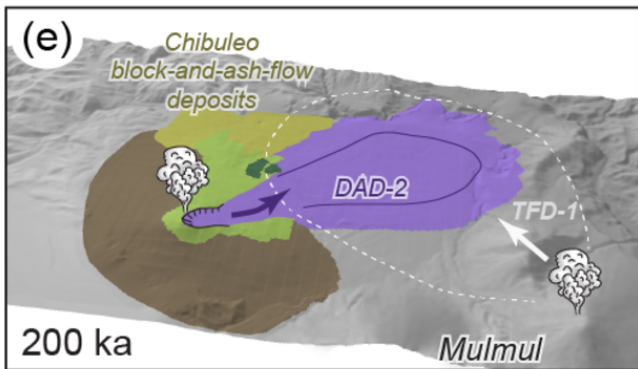
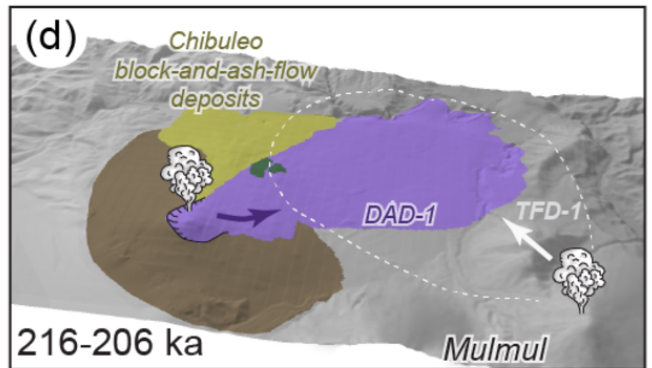
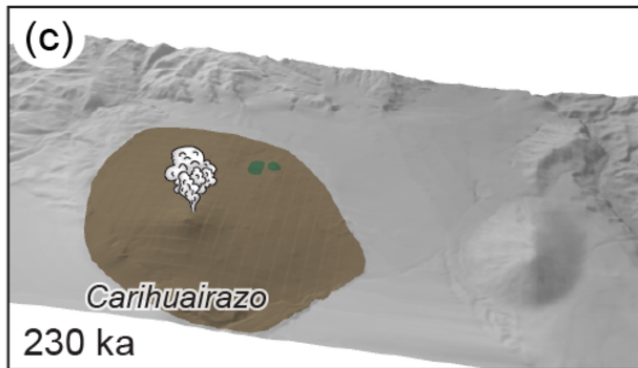
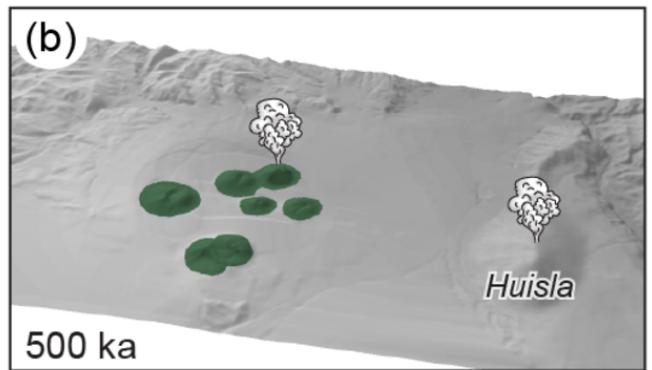
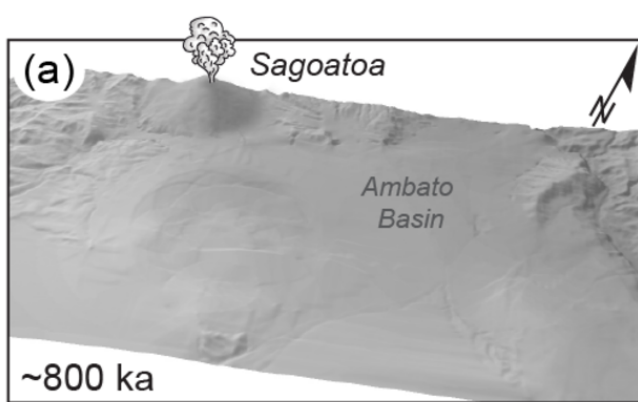














Sample No.	CAR14	CAR15	RIO87A	RIO87B	RIO117	RIO118	16EQ45	16EQ49	16EQ51	CAR69	16EQ31	CAR62A	CAR60	16EQ48	16EQ50	CAR13A	RIO81A	CAR11A	CAR09A	CAR09C	CAR11C	17EQ115
Unit	Old lava domes	Old lava domes	Basal lava flows	Basal lava flows	Basal lava flows	Basal lava flows	Basal lava flows	Intermediate lava flows	Intermediate lava flows	Intermediate lava flows	Intermediate lava flows	Terminal edifice	Terminal edifice	Terminal edifice	Terminal edifice	Chibuleo BAFD	Chibuleo BAFD	DAD	DAD	DAD	BAFD	BAFD
UTM Easting <sup>+</sup>	753880	753414	747041	747041	754241	753541	751507	748257	749690	750416	753781	754096	755579	748369	749690	754837	746841	761450	763787	763787	761450	759985
UTM Northing <sup>+</sup>	9851818	9851471	9843725	9843725	9841025	9840625	9845930	9844399	9844487	9850179	9847553	9845243	755579	9855162	9844256	9854964	9854025	9856808	9852012	9852012	9856808	9855162
Location	Sunantza dome	Cruz Maqui dome	Piedra Negra lava flow, SW flank	Piedra Negra lava flow, SW flank	Lava flow, SE flank	Lava flow, SE flank	Pachanlica valley lava flow	Lava flow, W flank	BAFD, W flank	Lava flow, N flank	Lava, Punta Tumbuso	Sta Rosa dome	Cerro Pitiunga dome	Young lava flow, W flank	Lava flow, Terminal cone	Chibuleo BAFD	Tundahua BAFD	DAD-1, Bellavista section	DAD-2, El Carmen section	DAD-3, El Carmen section	L-BAFD, Bellavista section	L-BAFD, San Vicente section
<b>SiO2</b>	59.63	62.23	60.70	61.25	61.50	61.20	59.17	60.55	62.03	60.07	60.61	63.68	61.06	59.14	58.94	59.87	60.70	61.29	62.30	61.00	61.45	62.39
<b>TiO2</b>	0.76	0.64	0.71	0.69	0.68	0.75	0.63	0.69	0.58	0.68	0.69	0.60	0.73	0.74	0.67	0.71	0.71	0.60	0.52	0.59	0.58	0.59
<b>Al2O3</b>	17.52	17.31	17.10	17.15	17.65	17.40	16.55	17.15	16.43	18.86	18.03	16.66	16.80	17.21	16.52	16.88	17.08	17.58	17.46	17.19	17.82	17.20
<b>Fe2O3*</b>	6.44	5.57	6.12	5.97	5.73	6.00	6.00	5.96	5.19	6.05	6.34	5.00	6.10	6.54	6.02	5.96	6.18	5.77	5.09	5.25	5.82	5.62
<b>MnO</b>	0.10	0.09	0.09	0.09	0.08	0.09	0.09	0.09	0.08	0.10	0.10	0.08	0.09	0.10	0.09	0.10	0.09	0.10	0.09	0.09	0.10	0.10
<b>MgO</b>	3.51	2.41	2.92	2.85	2.07	2.90	3.86	2.88	2.57	2.33	2.34	2.45	3.48	3.08	3.34	3.12	3.08	2.52	1.68	2.13	2.00	2.16
<b>CaO</b>	6.11	5.01	5.52	5.50	5.35	5.60	6.19	5.82	5.30	5.94	5.99	4.74	5.59	6.06	6.08	5.89	5.92	5.75	5.02	5.24	5.61	5.46
<b>Na2O</b>	4.41	4.58	4.41	4.40	4.50	4.51	4.12	4.17	4.29	4.65	4.38	4.61	4.26	4.28	3.84	4.36	4.46	4.42	4.82	4.24	4.33	4.08
<b>K2O</b>	1.31	1.53	1.47	1.45	2.28	1.43	1.19	1.40	1.46	1.37	1.36	1.64	1.52	1.30	1.45	1.38	1.21	1.33	1.45	1.65	1.40	1.36
<b>P2O5</b>	0.22	0.20	0.20	0.18	0.21	0.20	0.19	0.18	0.20	0.18	0.23	0.16	0.21	0.22	0.18	0.20	0.22	0.20	0.24	0.19	0.23	0.22
<b>LOI</b>	0.12	0.37	0.23	0.21	0.06	0.10	0.71	-0.04	0.13	0.02	0.24	0.00	0.02	-0.08	1.59	1.36	0.22	-0.09	0.72	1.43	0.67	0.58
<b>Total</b>	100.13	99.94	99.47	99.76	100.11	100.18	98.71	98.86	98.25	100.29	100.29	99.61	99.86	98.59	98.73	99.82	99.87	99.46	99.38	99.00	100.00	99.75
<b>Sc</b>	13.17	10.96	10.50	10.50	8.70	10.80	13.98	12.68	9.99	9.47	10.05	8.52	12.30	12.00	13.58	13.19	13.80	10.58	6.67	8.80	8.07	9.02
<b>V</b>	146.54	92.06	137.00	134.00	118.00	133.00	135.44	140.85	116.00	121.47	130.69	106.77	134.09	147.75	177.39	143.59	154.00	123.03	70.52	101.87	99.84	110.36
<b>Cr</b>	53.58	11.55	38.00	38.00	11.00	27.00	116.10	19.37	27.03	4.76	6.10	37.96	73.51	26.59	47.03	39.96	42.00	12.78	4.09	10.39	5.88	11.41
<b>Co</b>	20.72	15.00	16.00	19.00	13.00	17.00	18.43	16.32	14.44	14.89	16.03	15.01	19.61	18.38	19.50	17.09	18.00	14.61	9.25	12.75	12.10	14.70
<b>Ni</b>	46.72	18.76	36.00	28.00	10.00	29.00	65.63	27.77	25.86	7.64	7.52	29.25	47.83	32.79	41.45	33.34	38.00	18.39	4.88	9.78	5.53	9.20
<b>Rb</b>	17.03	29.36	29.50	29.00	34.50	22.50	25.23	32.32	35.30	24.80	30.22	47.46	49.07	29.37	32.96	24.83	20.00	24.87	24.95	42.16	32.00	31.55
<b>Sr</b>	692.38	598.99	604.00	608.00	666.00	645.00	584.10	586.01	609.68	712.66	677.36	571.88	597.45	602.18	595.16	749.79	795.00	604.77	650.07	609.99	664.67	649.86
<b>Y</b>	11.41	11.95	12.20	12.00	11.70	13.00	12.73	11.94	9.99	12.83	11.91	9.02	10.47	13.13	11.37	12.93	12.00	11.74	11.39	11.37	11.96	10.86
<b>Zr</b>	104.51	77.02	116.00	132.00	123.00	112.00	97.80	108.64	39.60	111.41	113.13	65.36	101.94	114.69	106.40	95.95	83.00	78.41	86.81	98.36	105.98	94.24
<b>Nb</b>	4.56	4.60	4.70	5.20	4.80	4.80	4.00	4.08	4.41	4.61	4.84	4.74	4.39	4.85	4.48	4.39	4.00	4.28	4.57	4.45	4.36	4.28
<b>Ba</b>	610.68	709.74	662.00	685.00	628.00	670.00	614.06	669.87	836.43	593.08	598.15	705.67	668.03	614.39	661.57	581.14	615.00	593.93	655.49	668.36	592.90	626.59
<b>La</b>	13.06	14.78	14.50	14.50	15.70	15.00	12.27	14.80	14.69	14.16	13.66	14.16	13.66	14.02	13.70	13.76	14.00	12.00	13.87	13.93	13.74	13.29
<b>Ce</b>	26.87	32.11	30.50	31.00	30.00	30.50	23.25	29.85	30.72	29.65	29.28	26.33	30.37	28.13	27.65	27.76	29.00	27.01	29.97	30.99	31.17	28.48
<b>Nd</b>	15.52	15.77	17.00	17.00	17.00	17.50	13.74	15.92	14.56	16.93	15.62	14.33	14.77	16.72	14.61	16.09	16.00	13.80	15.66	15.04	15.68	14.13
<b>Sm</b>	3.46	3.21	3.40	3.35	3.70	3.70	2.88	3.22	2.97	3.58	3.24	2.88	3.04	3.45	3.16	3.41	3.35	2.92	3.38	3.19	3.59	2.93
<b>Eu</b>	1.02	1.01	1.02	1.03	0.98	1.03	0.82	0.96	0.93	1.09	1.03	0.82	0.97	1.17	0.78	0.96	0.99	0.85	1.00	0.92	1.04	0.95
<b>Gd</b>	2.87	3.36	3.20	3.20	3.00	3.50	2.61	2.36	2.68	3.00	3.39	2.36	3.09	3.06	2.42	3.08	3.20	3.01	3.16	3.10	3.32	2.60
<b>Dy</b>	2.06	1.98	2.20	2.20	2.15	2.35	2.15	2.29	1.77	2.24	2.09	1.71	1.93	2.44	2.06	2.16	2.15	1.95	1.86	2.06	2.12	2.01
<b>Er</b>	0.32	0.03	1.15	1.10	1.10	1.20	1.14	1.24	0.85	0.38	1.00	0.00	-0.01	1.15	0.77	0.79	1.10	-0.04	0.14	-0.05	-0.03	1.25
<b>Yb</b>	0.97	1.08	1.05	1.02	0.97	1.12	1.00	0.88	0.59	1.14	1.02	0.72	0.95	0.92	0.80	1.16	0.98	1.09	1.01	0.99	1.07	0.96
<b>Th</b>	2.43	3.41	3.30	3.30	3.70	3.00	2.29	3.04	2.60	2.25	3.28	3.36	2.91	2.58	2.80	2.58	2.60	1.77	2.40	2.58	2.36	2.45

<sup>+</sup> WGS84, 17 zone

\* all Feo as Fe2O3

Sample	Unit	Location	UTM Easting	UTM Northing	Phase	K (%)	<sup>40</sup> Ar* (%)	<sup>40</sup> Ar* x 10 <sup>11</sup> (at/g)	Age ± 1σ (ka)	Mean age (ka)
16EQ45	Basal lava flows	Lava flow, inside the avalanche scar, NE flank	751,507	9,845,930	Groundmass	1.152	2.80	2.5938	216 ± 8	217 ± 9
							2.59	2.6197	218 ± 9	
17EQ115	L-DAFD	Juvenile block from a block-and-ash-flow deposit	759,985	9,855,162	Groundmass	1.741	3.73	3.7811	208 ± 4	206 ± 4
							6.16	3.7181	204 ± 4	
16EQ49	Basal lava flows	Proximal lava flow/dome, W flank	748,257	9,844,399	Groundmass	1.682	4.89	3.5067	200 ± 5	199 ± 5
							4.69	3.4962	199 ± 5	
16EQ51	Basal lava flows	Juvenile block from a summit block-and-ash-flow	749,690	9,844,487	Groundmass	1.471	3.07	3.0723	200 ± 7	198 ± 7
							2.78	3.0216	197 ± 8	
16EQ31	Basal lava flows	Lava flow, NE flank	753,781	9,847,553	Groundmass	1.463	7.17	3.0679	201 ± 4	197 ± 4
							9.29	2.9641	194 ± 3	
					Plagioclase	0.356	2.22	0.7029	189 ± 9	187 ± 9
							2.18	0.6837	184 ± 9	
CAR69	Basal lava flows	Lava flow, N flank	750,425	9,850,188	Groundmass	1.322	6.11	2.5872	187 ± 4	186 ± 5
							3.97	2.5833	187 ± 5	
							5.15	2.5392	184 ± 4	
					Plagioclase	0.377	1.87	0.7212	183 ± 10	178 ± 11
							1.60	0.6760	172 ± 11	
CAR60	Terminal edifice	Pitiunga lava dome, E flank, Pachanlica valley	755,588	9,845,772	Groundmass	1.663	6.89	3.0625	176 ± 4	176 ± 10
							5.34	3.2221	185 ± 4	
							4.45	2.8672	165 ± 4	
16EQ50	Terminal edifice	Lava flow, summit pyramide	749,690	9,844,256	Groundmass	1.852	2.60	3.3111	171 ± 7	172 ± 7
							2.45	3.3279	172 ± 7	
16EQ48	Terminal edifice	Juvenile fragment of dome breccia	748,369	9,855,162	Groundmass	1.473	3.08	2.5013	163 ± 6	157 ± 5
							3.33	2.3463	153 ± 5	

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Sample No.	Lab code	Locality	UTM Easting	UTM Northing	Unit	Sample type	<sup>14</sup> C age (years BP)
CAR-09M	GrA 46688	El Carmen	763787	9852012	Paleosoil below TFD-2	charcoal	39030 +440/-380
CAR-09N	GrA 48843	El Carmen	763787	9852012	Paleosoil below TFD-2	charcoal	> 45000
CAR-10F	GrA 48875	San Vicente	760098	9855155	L-BAFD	charcoal	> 45000

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		Age max.	Age min.	Duration	Raw volume	Total volume	Eruptive rate		Erosion rate	
		ka	ka	ka	km <sup>3</sup>	km <sup>3</sup>	km <sup>3</sup> /kyr	mm/yr	km <sup>3</sup> /kyr	mm/yr
Construction phase of Carihuairazo	Without erosion correction	223 ± 6*	157 ± 5	66 ± 8	85 ± 49		1.3 ± 0.8	5.3 ± 3.1		
	Considering eroded volume during the construction	223 ± 6*	157 ± 5	66 ± 8		97 ± 53	1.5 ± 0.9	6.1 ± 3.6		
Erosion phase	Since the end of Carihuairazo construction	157 ± 5	0	157 ± 5	18 ± 5				0.12 ± 0.03	0.48 ± 0.13
	Considering eroded volume during the construction	157 ± 5	0	157 ± 5		30 ± 9			0.14 ± 0.04	0.56 ± 0.16
	Volume eroded during the construction	223 ± 6	157 ± 5	66 ± 8		12 ± 4				