



HAL
open science

The eruptive chronology of the carihuaairazo volcano (Ecuador): Recurrent sector collapses of a Middle Pleistocene stratovolcano of the northern andes

Pablo Samaniego, Jorge Ordóñez, Mathilde Bablon, Minard Hall, Xavier Quidelleur, Pierre Lahitte, Santiago Santamaria, Céline Liorzou

► 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

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

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

3

4 Pablo Samaniego¹, Jorge Ordóñez^{2,*}, Mathilde Bablon^{3,4}, Minard L. Hall²,
5 Xavier Quidelleur⁴, Pierre Lahitte⁴, Santiago Santamaria^{2,4}, Céline Liorzou⁵

6

7 ¹ Université Clermont Auvergne, CNRS, IRD, OPGC, Laboratoire Magmas et Volcans,
8 F-63000 Clermont-Ferrand, France

9 ² Instituto Geofísico, Escuela Politécnica Nacional, Ladrón de Guevara E11-253, Ap.
10 2759, Quito, Ecuador

11 ³ Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur, 250
12 rue Albert Einstein, Sophia Antipolis 06560 Valbonne, France.

13 ⁴ Université Paris-Saclay, CNRS, Laboratoire GEOPS, Rue du Belvédère, 91405 Orsay,
14 France

15 ⁵ Laboratoire Géosciences Océan, Institut Universitaire Européen de la Mer, Université
16 de Bretagne Occidentale, Rue Dumont d'Urville, 29280 Plouzané, France

17

18 Corresponding author: pablo.samaniego@ird.fr

19

20 * Now at: Dirección Metropolitana de Gestión de Riesgos, Secretaria de Seguridad y
21 Gobernabilidad, Municipio de Quito

22

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

24

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}K - ^{40}Ar , ^{14}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 ± 4 and 216 ± 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}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}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 μm 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- σ 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 ± 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}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 CO_2 absorbed during the previous steps. Variable amounts of the dried sample were
180 used to obtain, after combustion, a CO_2 volume equivalent to at least 1 mg of C. Then,
181 CO_2 is reduced by H_2 in the presence of iron powder. ^{14}C activity is finally measured by
182 mass spectrometry. The ^{14}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 (ΔT_c) and quiescence (ΔT_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 (σ_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}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 ± 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 ± 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 ± 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.% SiO₂) 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.% SiO₂). 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 ⁴⁰Ar/³⁹Ar 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 ± 5 and 224 ± 5 ka (RIO117 and RIO118, respectively), and two samples from the
294 south-west flank dated at 213 ± 5 and 208 ± 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 ± 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.% 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 ± 5 and 198 ± 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 ± 4 ka, groundmass age of 16EQ31; Table 2) and
338 northern flanks (186 ± 5 ka; CAR69; Table 2 and Fig. 2a-b, and 3). Note that 16EQ31
339 sample was also dated at 187 ± 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 ± 4 ka. We stress these ages are slightly younger than that of the
342 Basal lava flows succession ranging from 224 ± 5 to 208 ± 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.% SiO₂) lava flows with
352 interlayered breccias (light brown-red unit, Fig. 3). Two ages were obtained on this
353 succession, yielding ages of 172 ± 7 and 157 ± 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 ± 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 ± 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 ± 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 ± 5 m over about 200
394 km² (Fig. 8), the volume of DAD-1 is estimated at 4 ± 1 km³.

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.% SiO₂). 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 ¹⁴C 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 km²
437 (Fig. 8), and, assuming an average thickness of 5-10 m, we propose a volume range of
438 0.5-1.0 km³. 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.% SiO₂). 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 km², quite similar to that of
472 the DAD-2. The average thickness of 8-10 m leads to an estimated volume of ~1 km³, 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 Carihuaairazo 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 km² 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 km³.

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.% SiO₂), 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 km³ 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.% SiO₂), 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.% SiO₂). 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 km³ (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 km³ 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.% SiO₂) 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.% SiO₂) 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.% SiO₂) 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.% SiO₂). 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 ± 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 20th 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 m³ 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.% SiO₂, with very few samples falling in the
679 field of basaltic andesites (55-56 wt.% SiO₂). 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.% SiO₂) that
688 clearly define a magmatic trend different than the Carihuairazo one, characterized by
689 higher K₂O 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 SiO₂), 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 K₂O and MgO vs. SiO₂, 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 ± 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 ± 5 ka; Bablon et al., 2020), and the overlaying L-BAFD (206 ± 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 ± 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 ± 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 ± 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 ± 6 and 157 ± 5 ka
831 (Samaniego et al., 2012; Table 2), and that the volume of emitted products reached $97 \pm$
832 53 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 km^3/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 ($66 \pm 6 \text{ ka}$), 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 $157 \pm 5 \text{ ka}$ (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 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 ± 4 and
884 216 ± 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 ¹⁴C 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 ± 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

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.

1128

1129

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

1131

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

1133

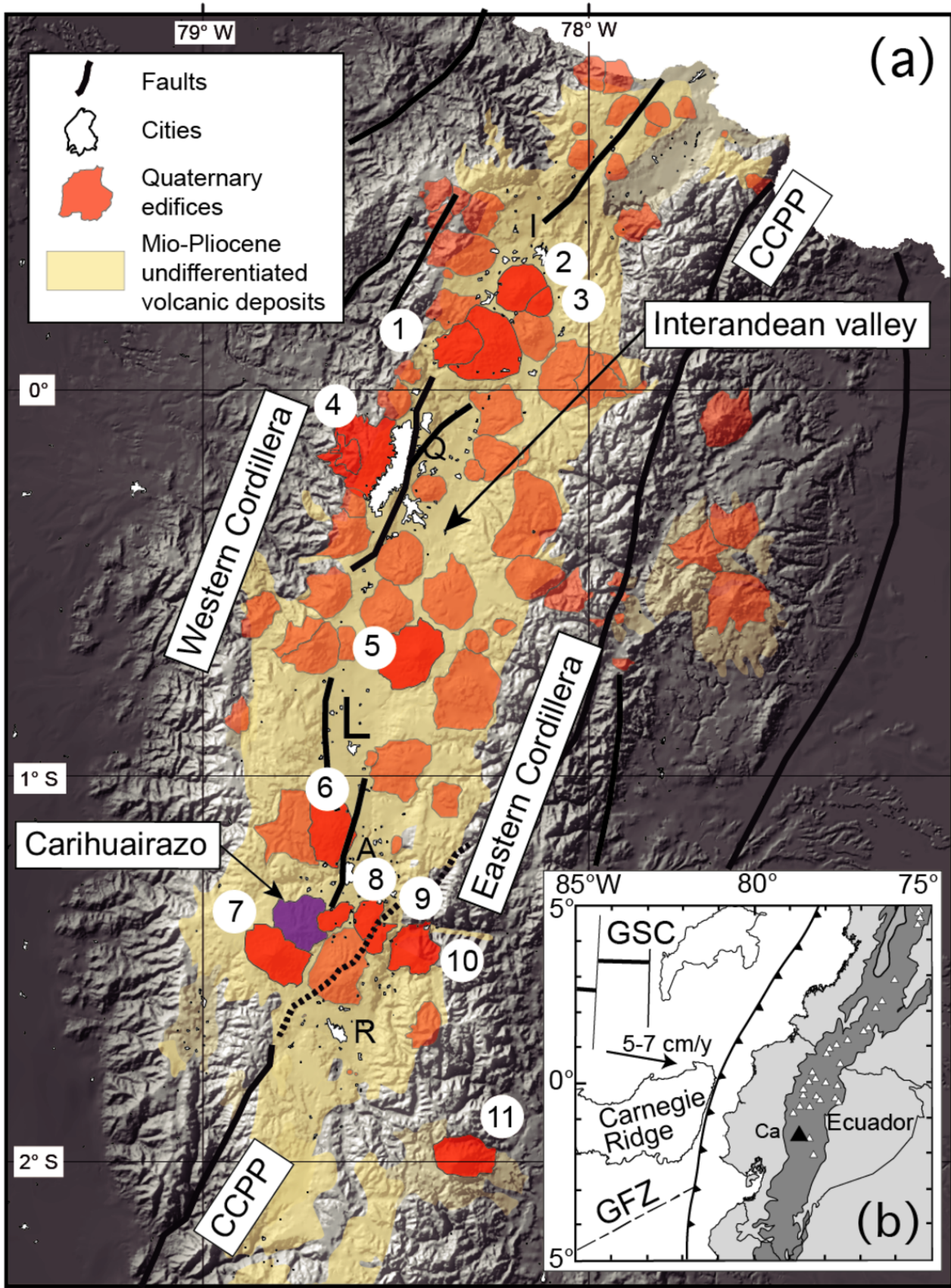
1134 **Table 3.** Radiocarbon ages for the Ambato basin deposits.

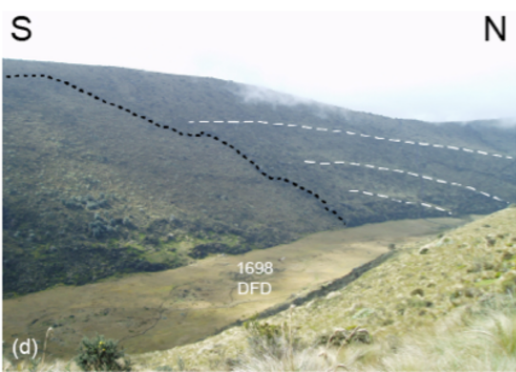
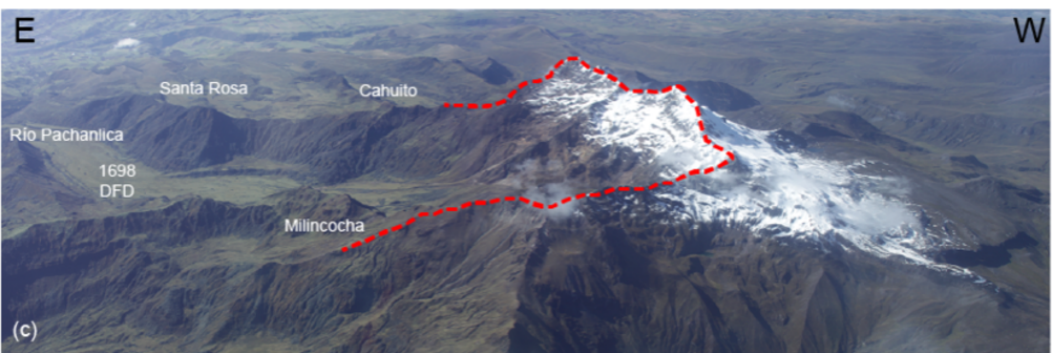
1135

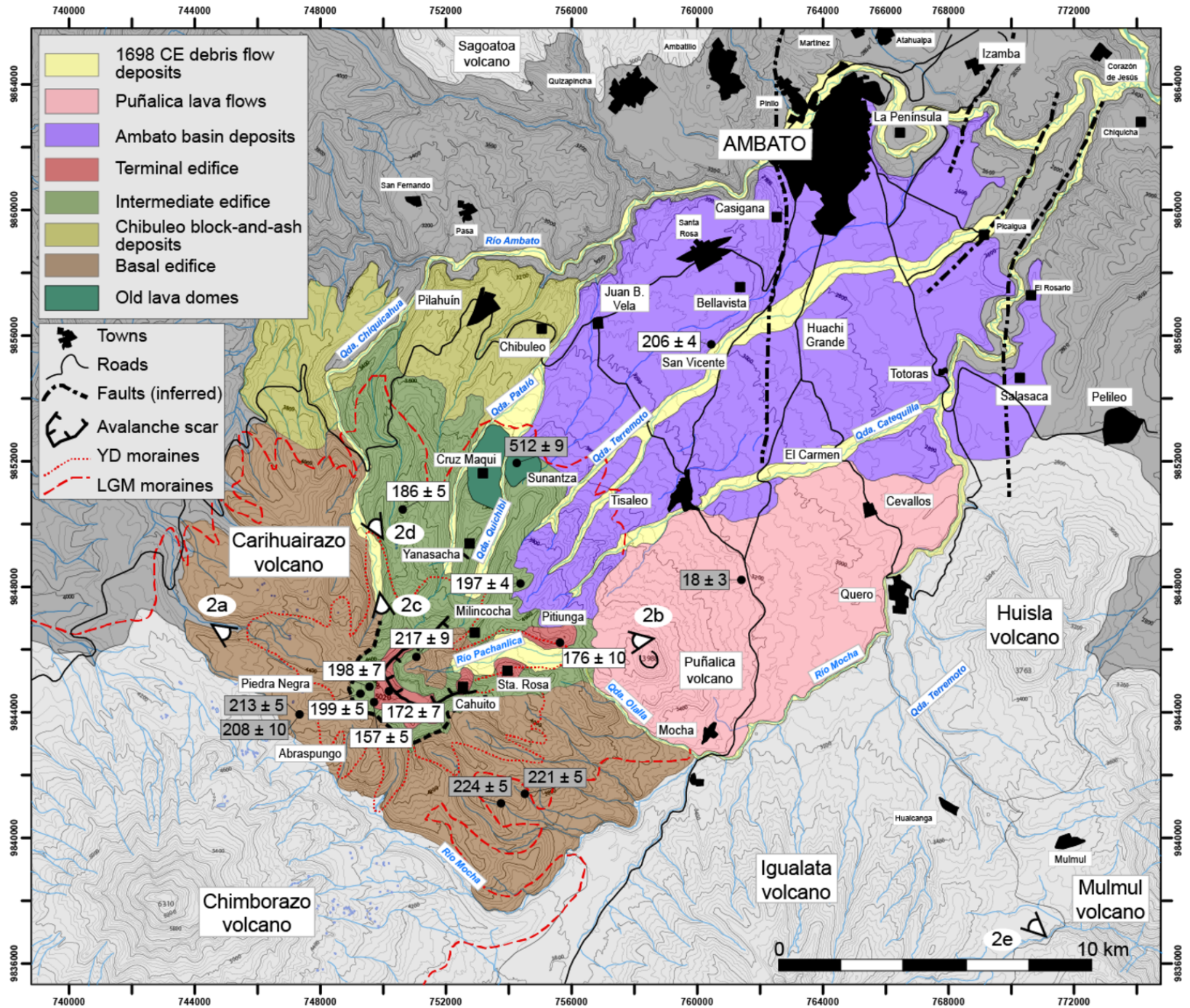
1136 **Table 4.** Results of volumes, eruptive and erosion rates calculations obtained from the
1137 numerical paleo-surfaces and given at 1-sigma accuracy. Raw volume corresponds to
1138 the volume calculated from the surface model without taking into account erosion that
1139 occurred during the construction. 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/m³ (Glicken,1991), and assuming a bulk density of
1145 2600 kg/m³ for the entire edifice. * Samaniego et al. (2012)

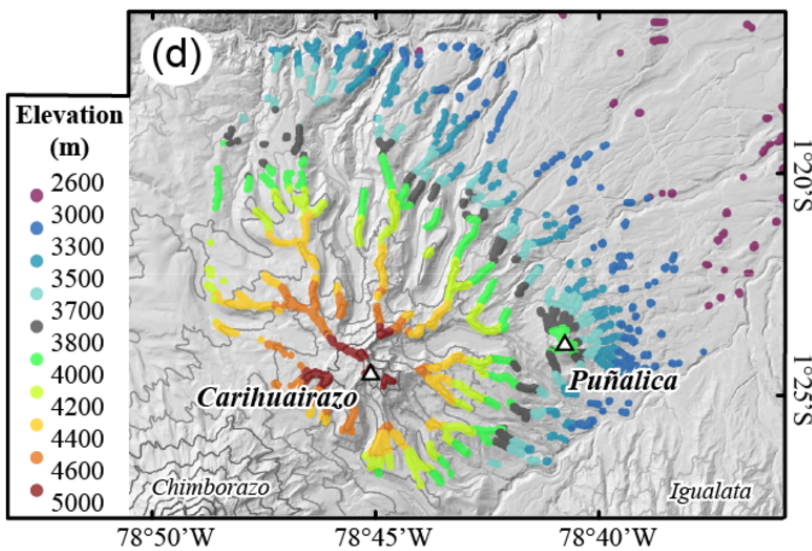
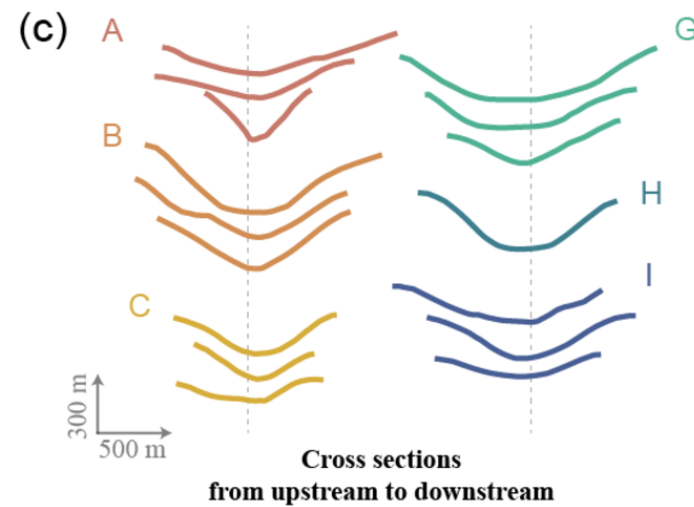
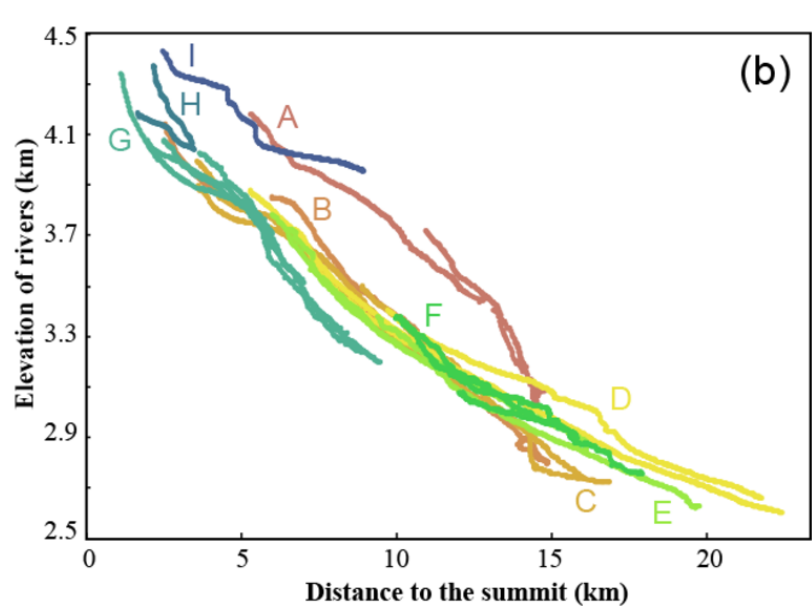
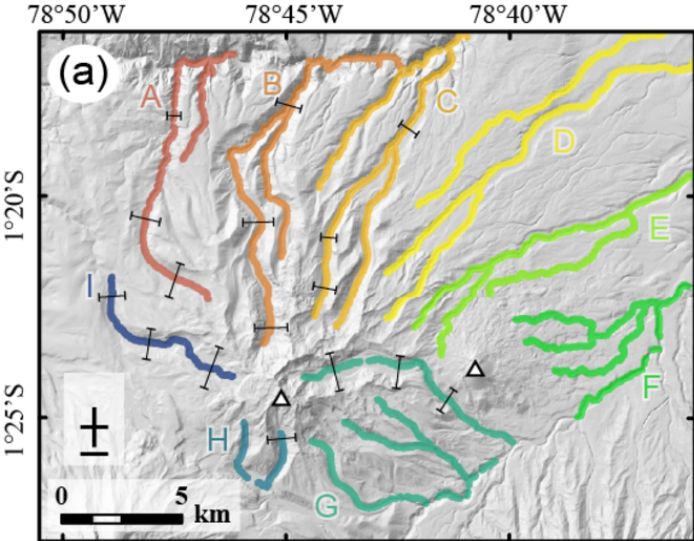
1146

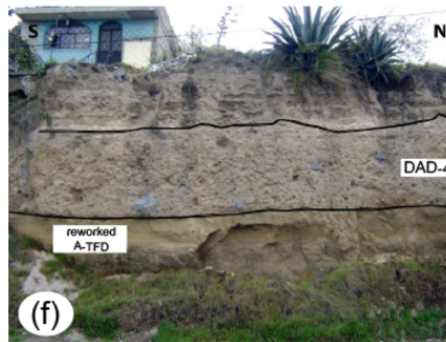
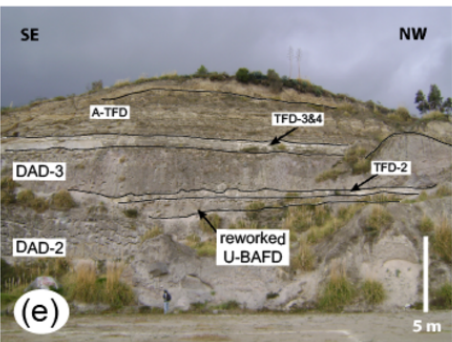
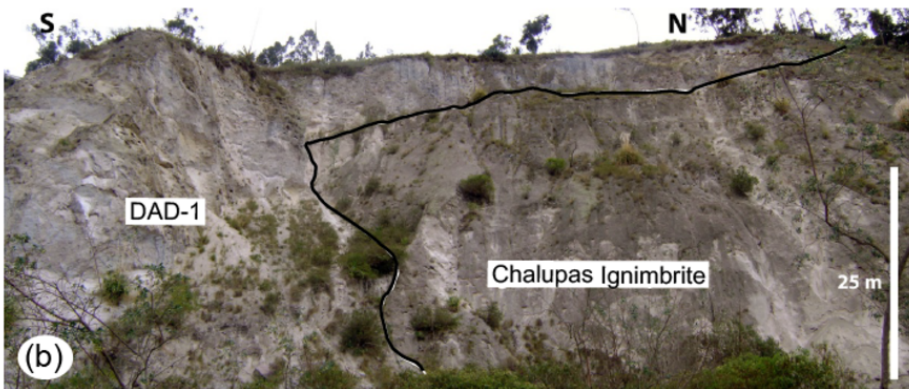
1147

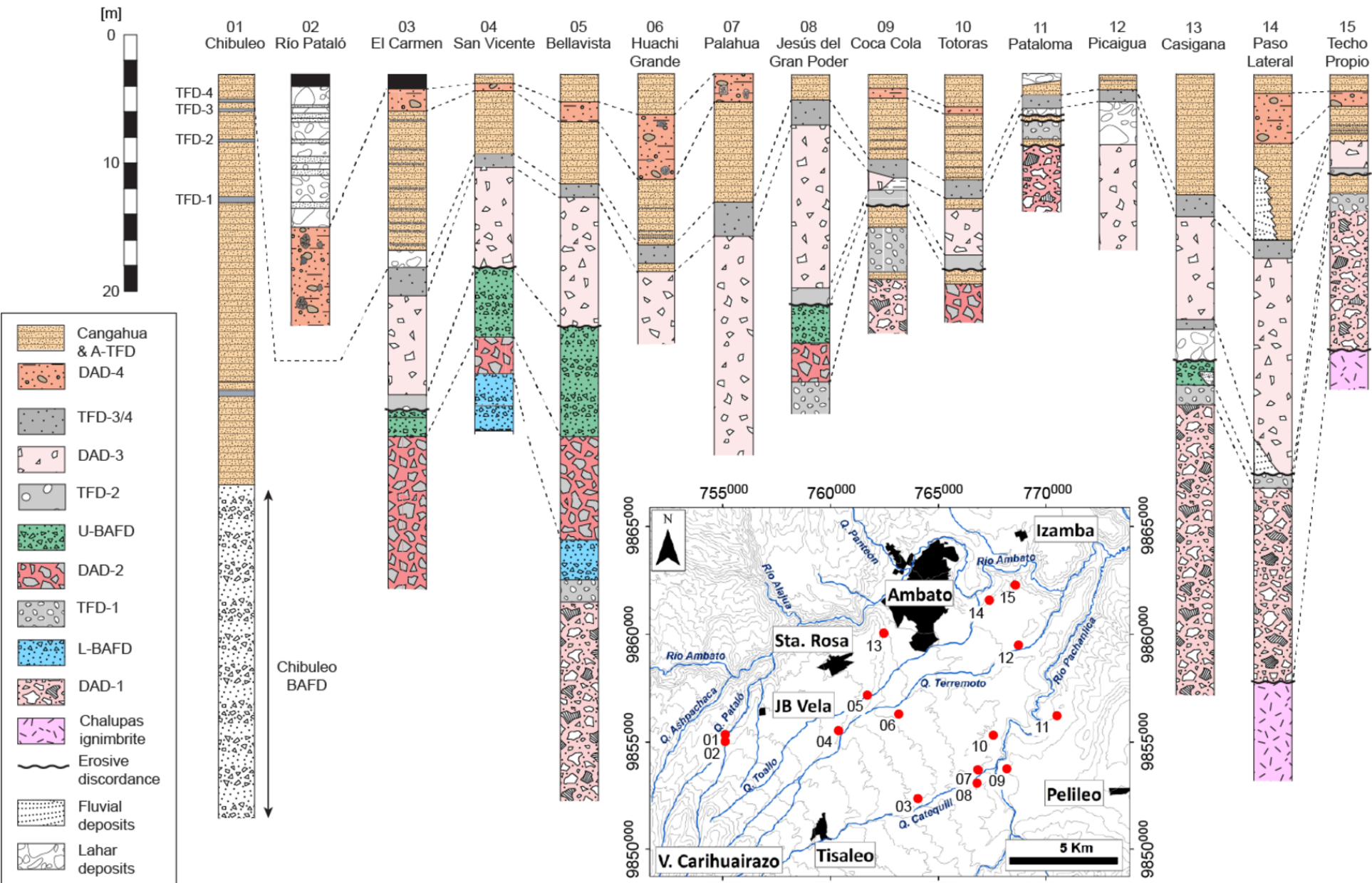


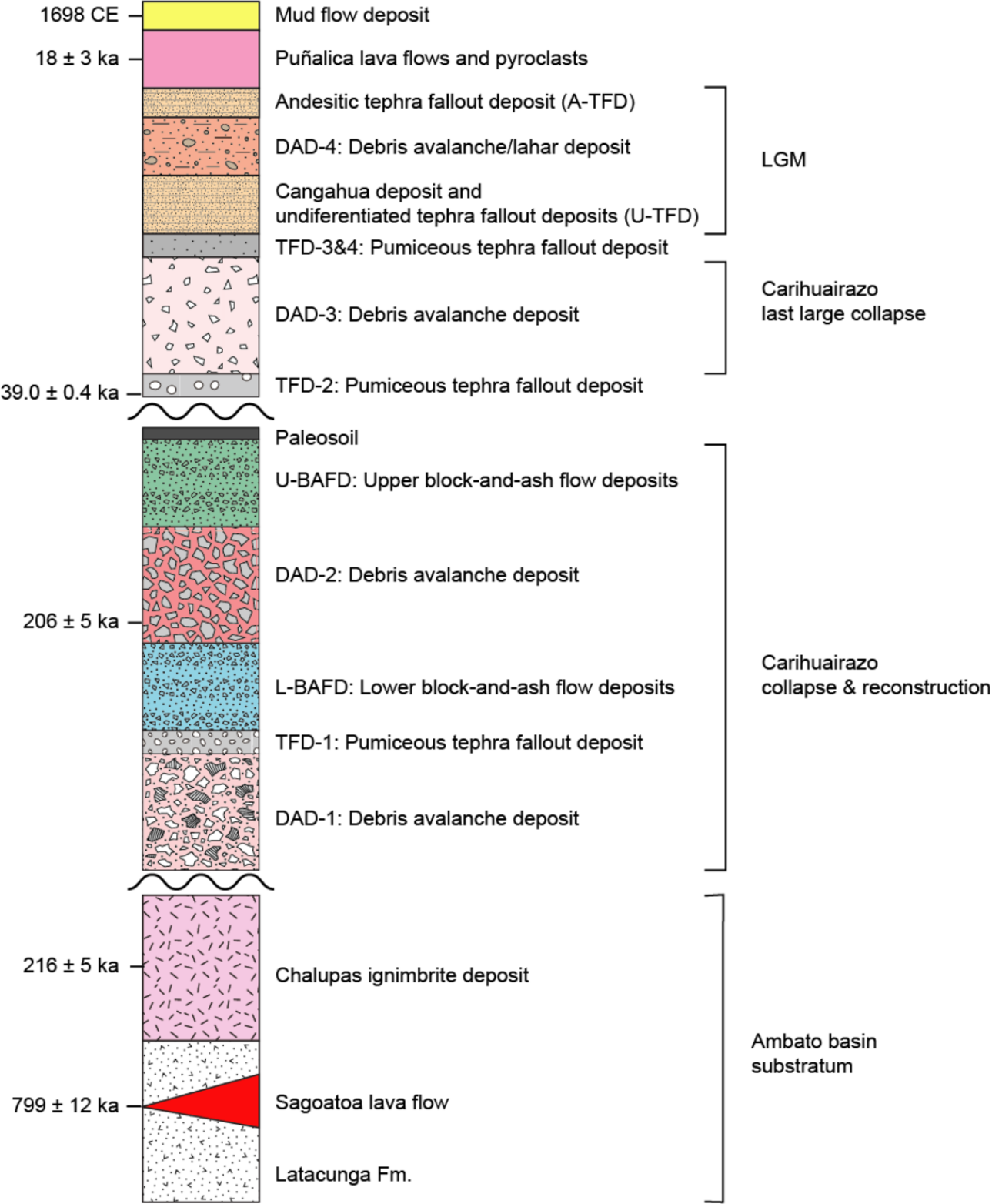


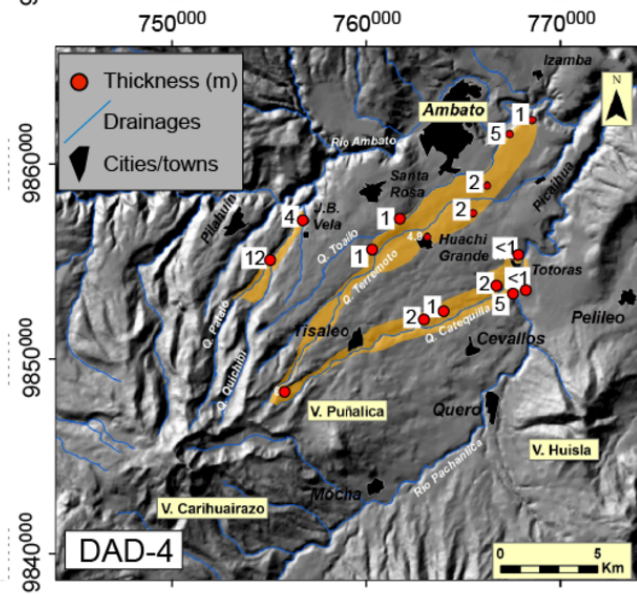
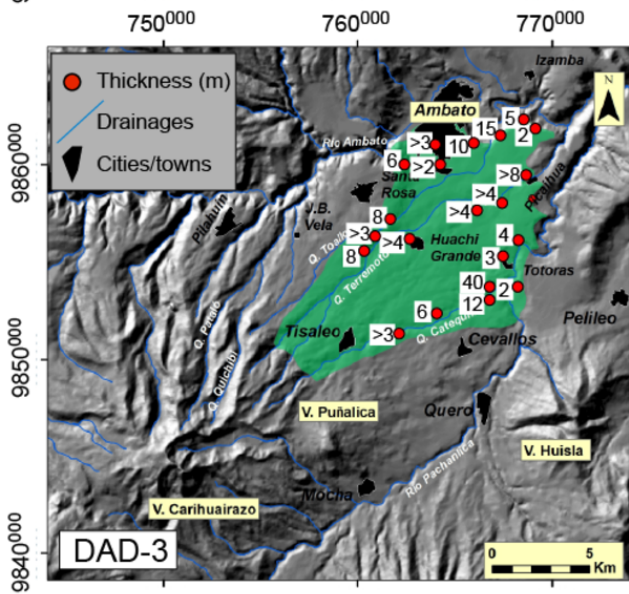
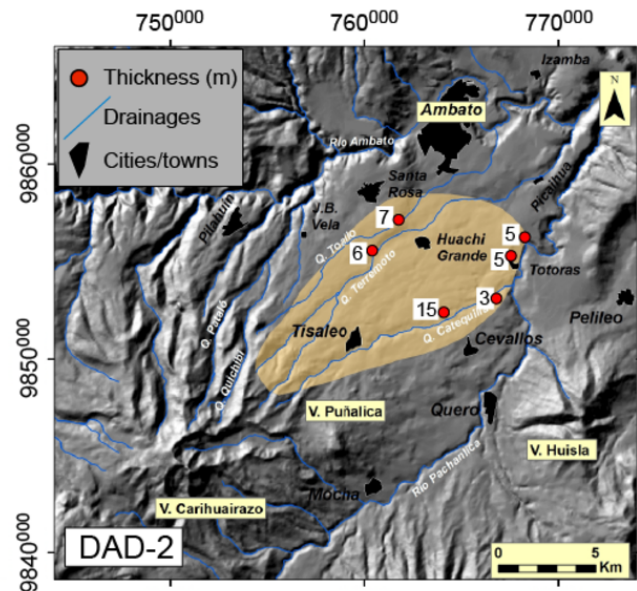
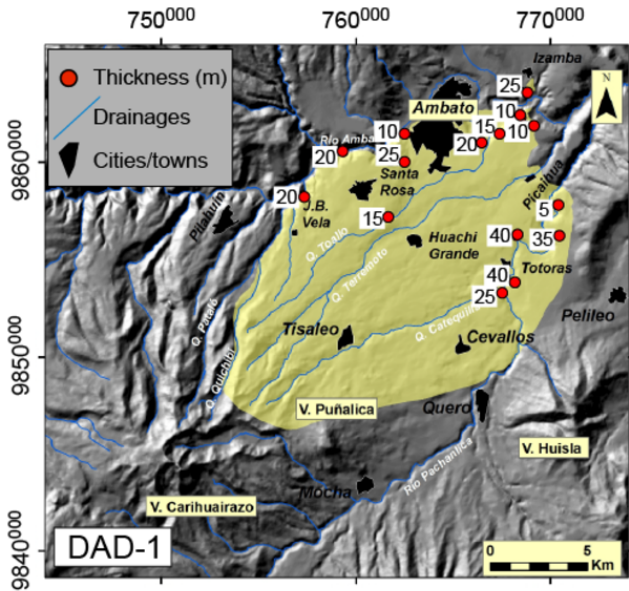


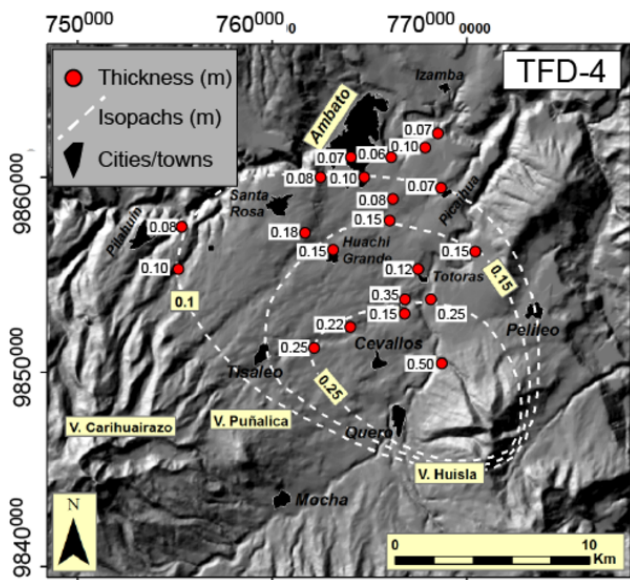
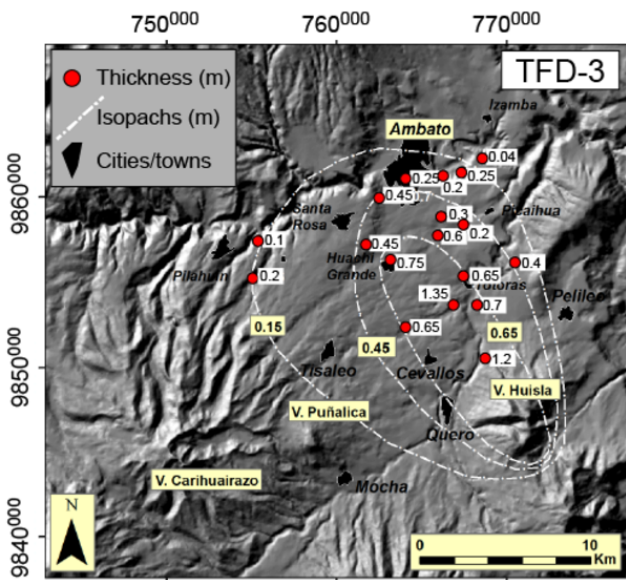
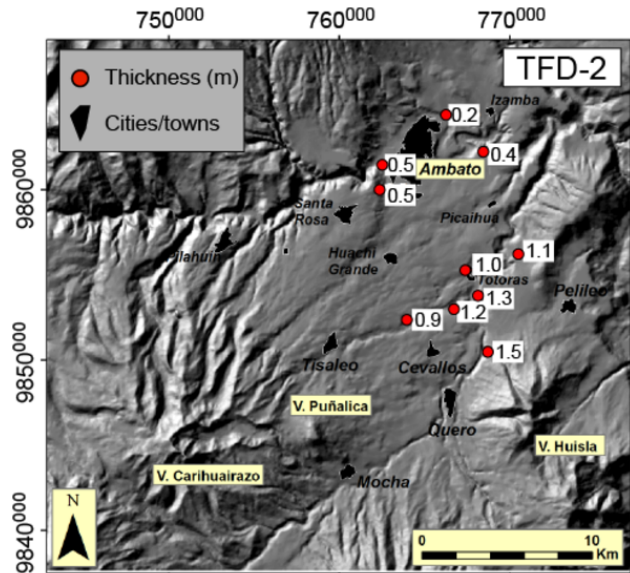
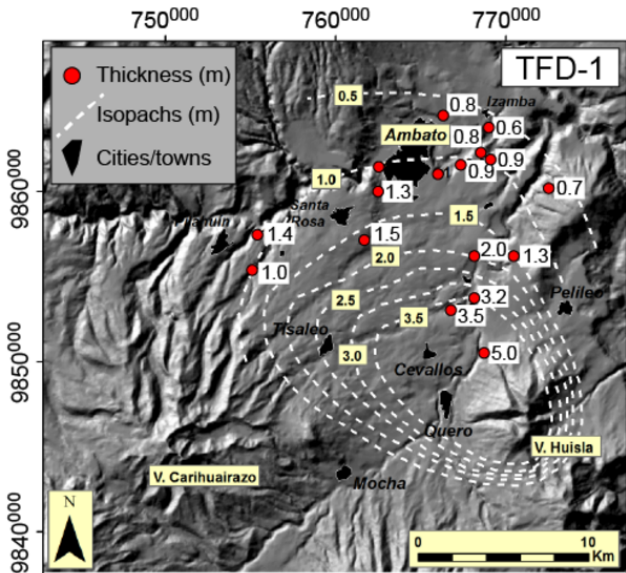


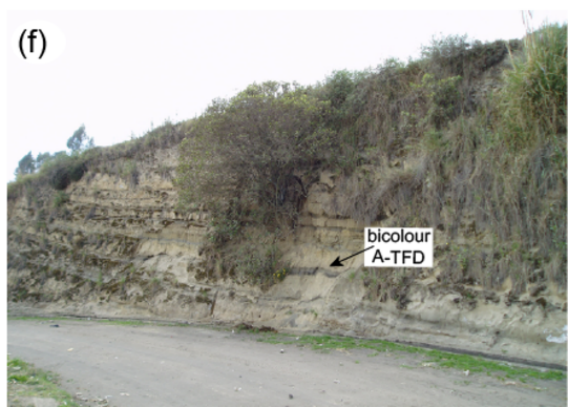
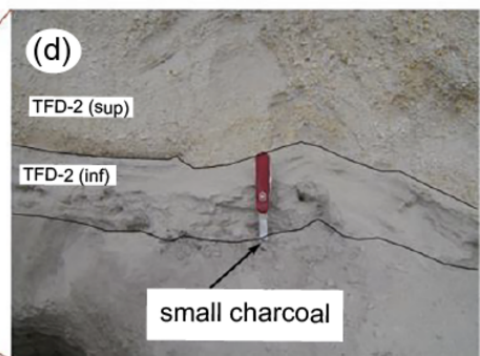
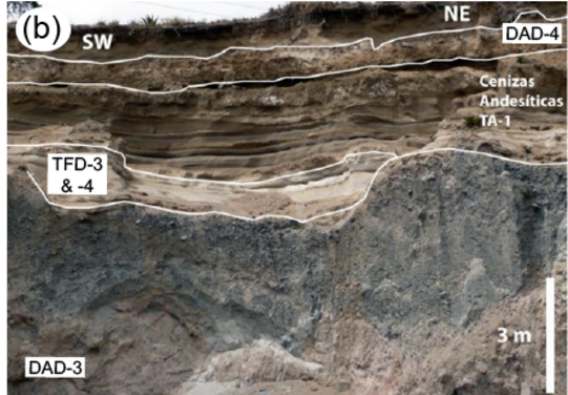
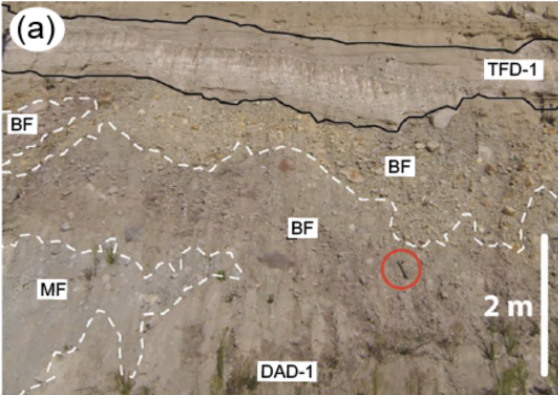


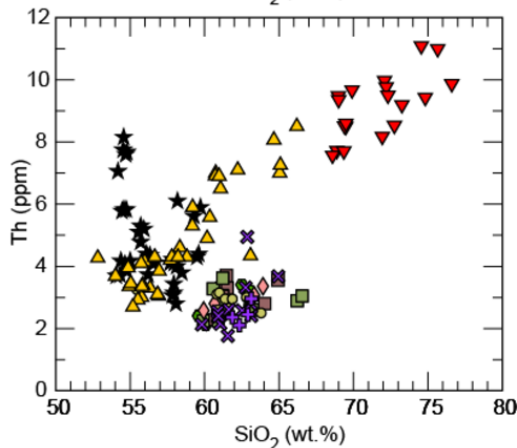
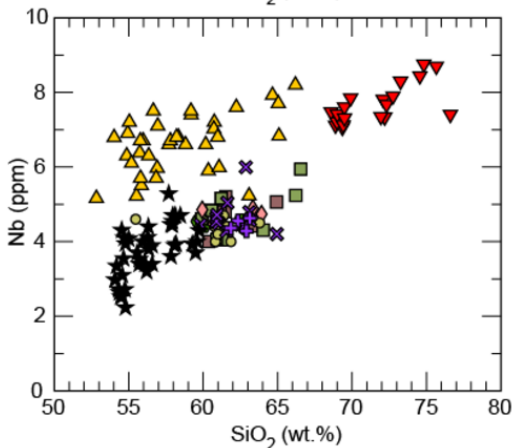
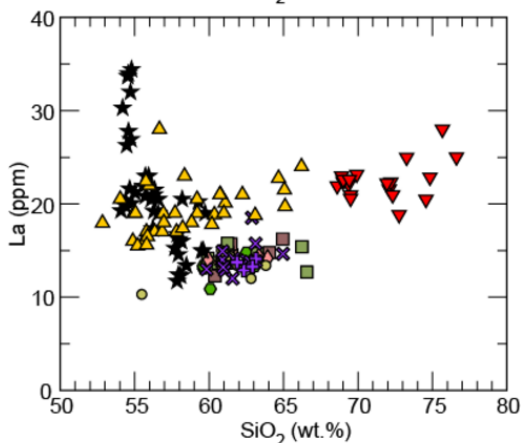
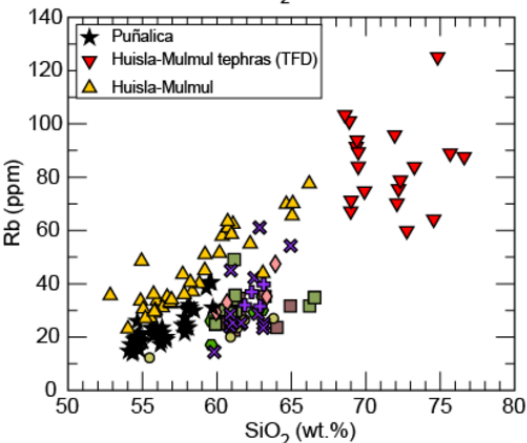
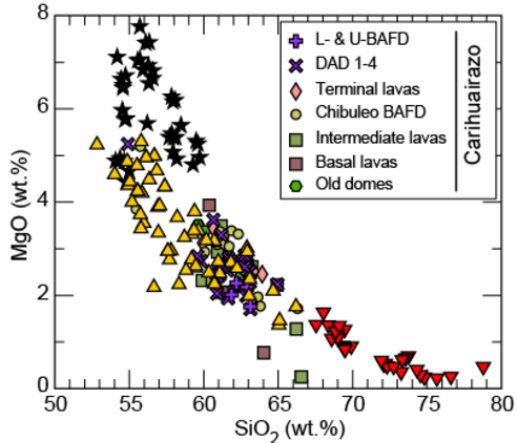
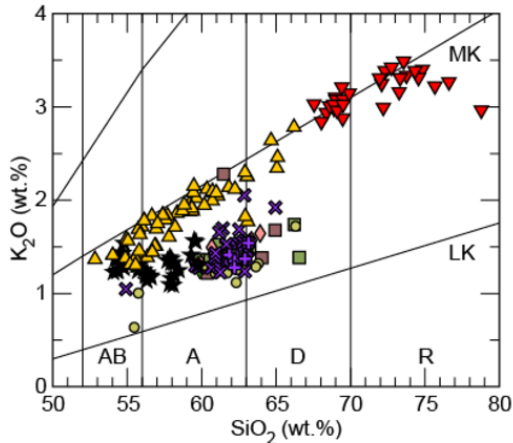


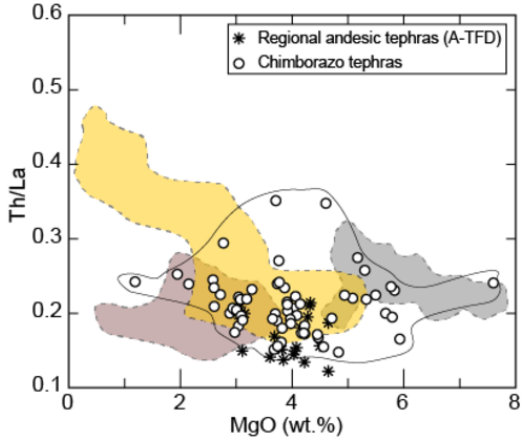
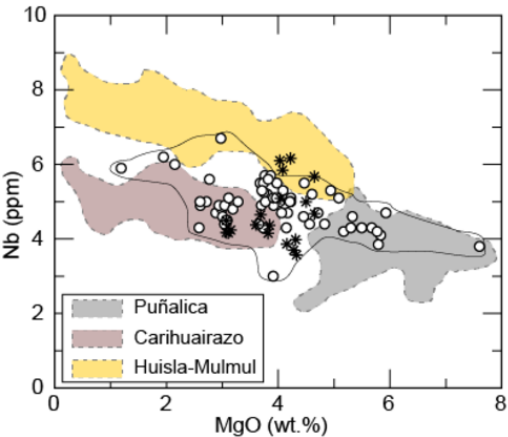


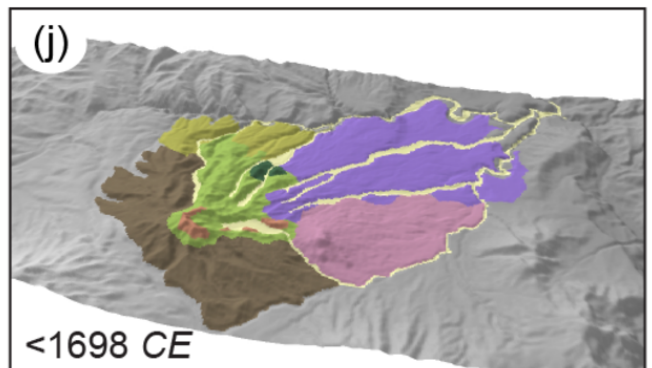
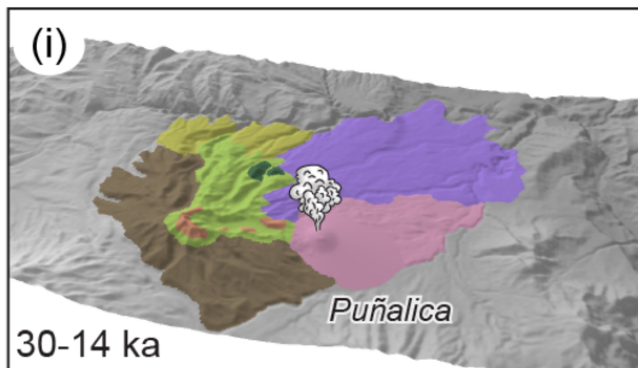
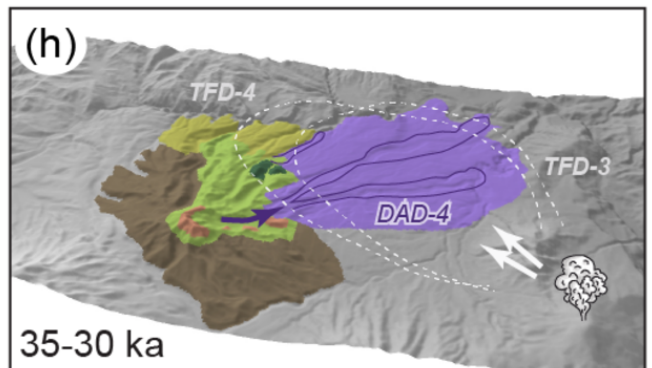
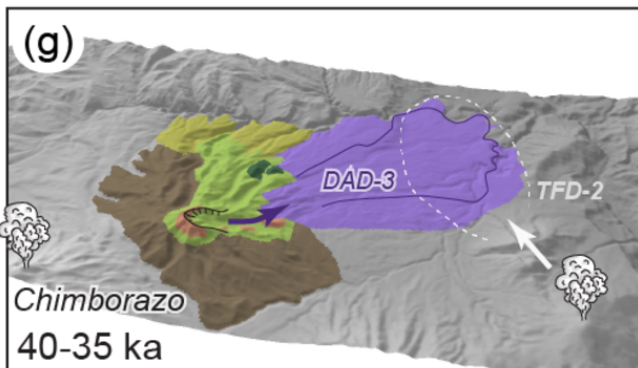
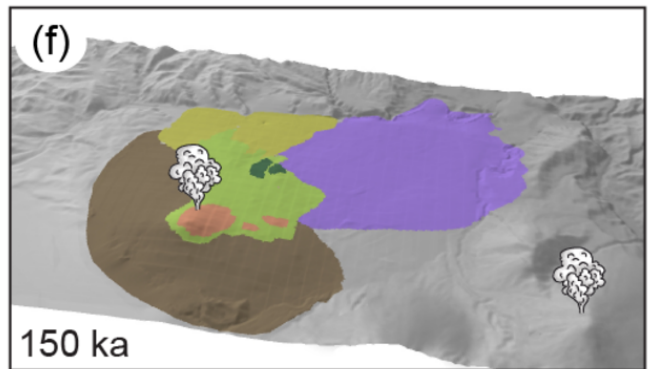
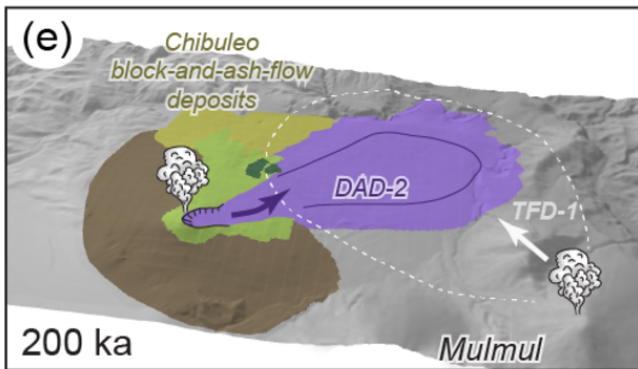
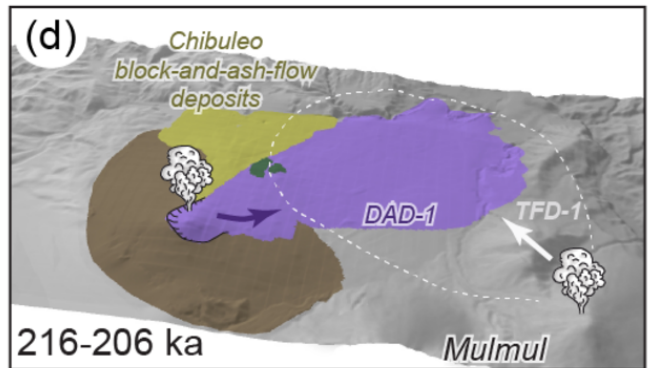
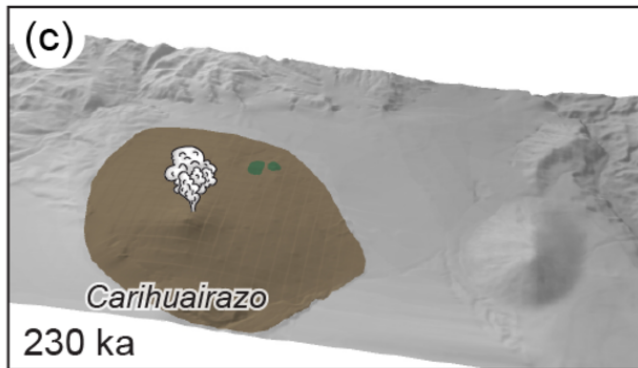
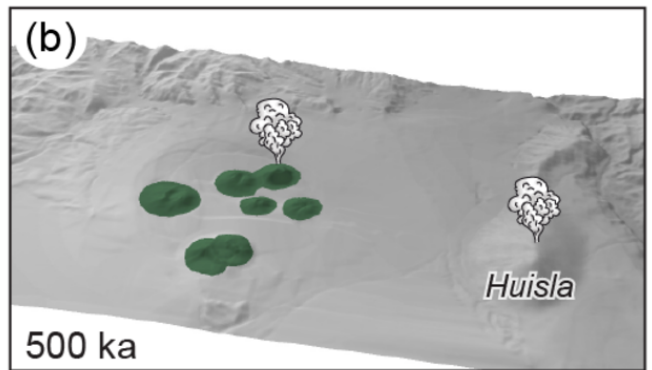
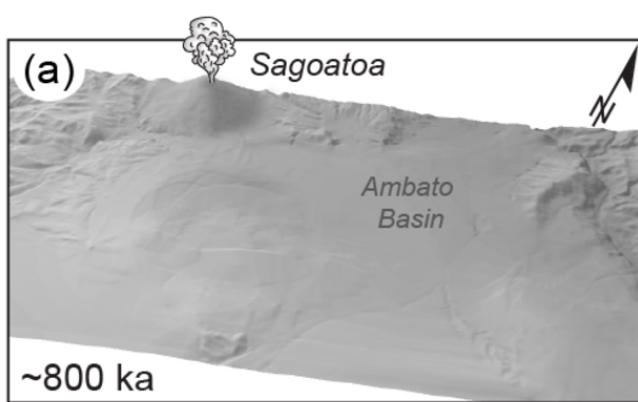












Sample No.	CAR14	CAR15	RIO87A	RIO87B	RIO117	RIO118	16EQ45	16EQ49	16EQ51	CAR69	16EQ31	CAR62A	CAR60	16EQ48	16EQ50	CAR13A	RIO81A	CAR11A	CAR09A	CAR09C	CAR11C	17EQ115
Unit	Old lava domes	Old lava domes	Basal lava flows	Basal lava flows	Basal lava flows	Basal lava flows	Basal lava flows	Intermediate lava flows	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 ⁺	753880	753414	747041	747041	754241	753541	751507	748257	749690	750416	753781	754096	755579	748369	749690	754837	746841	761450	763787	763787	761450	759985
UTM Northing ⁺	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
SiO2	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
TiO2	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
Al2O3	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
Fe2O3*	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
MnO	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
MgO	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
CaO	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
Na2O	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
K2O	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
P2O5	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
LOI	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
Total	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
Sc	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
V	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
Cr	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
Co	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
Ni	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
Rb	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
Sr	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
Y	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
Zr	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
Nb	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
Ba	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
La	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
Ce	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
Nd	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
Sm	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
Eu	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
Gd	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
Dy	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
Er	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
Yb	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
Th	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

⁺ WGS84, 17 zone

* all Feo as Fe2O3

Sample	Unit	Location	UTM Easting	UTM Northing	Phase	K (%)	⁴⁰ Ar* (%)	⁴⁰ Ar* x 10 ¹¹ (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	

Sample No.	Lab code	Locality	UTM Easting	UTM Northing	Unit	Sample type	¹⁴ 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

		Age max.	Age min.	Duration	Raw volume	Total volume	Eruptive rate		Erosion rate	
		ka	ka	ka	km ³	km ³	km ³ /kyr	mm/yr	km ³ /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				