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1 **Timing of Quaternary volcanism and its relationship with tectonics in the central**
2 **segment of the Ecuadorian Andes**

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17
18
19 **Keywords:**

- 20 - Ecuador
21 - K-Ar dating
22 - Quaternary
23 - Eruptive history
24 - Tectonics

25 **Highlights:**

- 26 - Volcanic activity in the central Ecuadorian Andes occurred since at least ~1.3 Ma
27 - An increase in volcanic activity took place to the south since ~0.6 Ma
28 - The predominance of older volcanoes to the north suggests an extension of volcanism
29 - Crustal tectonic structures had a key role in the spatial arrangement of volcanoes
30 - The overall volcanic output rate has been roughly stable during the last ~0.6 Ma

31

32 **ABSTRACT**

33 The unusually high number of volcanoes in the Ecuadorian Arc, located in the deformation
34 zone of the continental North Andean Sliver, coincides with the projection of the major oceanic
35 structures observed in the Nazca Plate, such as the Carnegie Ridge and the Grijalva fracture zone.
36 Although the relationship between this tectonic setting and volcanism has been widely discussed in the
37 literature, their temporal relationship has not been thoroughly investigated due to the lack of
38 geochronological data. We present here 20 new K-Ar and 2 $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained for 7 volcanoes of
39 the central segment of the Ecuadorian arc, which together with previous data show that volcanism in
40 this area started at ~ 1.3 Ma. A notable increase in volcanic activity occurred since ~ 0.6 Ma, when the
41 formation of a dozen volcanoes occurred in a relatively small area of the central segment. While this
42 arrangement of volcanoes, here referred to as a “volcanic cluster”, appears to be controlled by crustal
43 tectonic structures, the order of onset of these volcanoes and their eruptive activity does not show clear
44 migration patterns over time. However, the presence of older volcanoes in the north of the central
45 segment suggests a possible southward extension of volcanism between ~ 1.3 and ~ 0.6 Ma. Finally,
46 based on the cumulative bulk volumes calculated for the volcanic edifices over time, we infer that the
47 magmatic productivity rate has been roughly constant during the last ~ 550 kyr in this area.

48 1. INTRODUCTION

49 The Northern Andean Volcanic Zone results from the subduction of the oceanic Nazca Plate
50 beneath the northwestern margin of South America (Fig. 1a). In contrast to the narrow array of nearly
51 40 Quaternary volcanoes in Colombia, more than 80 Quaternary eruptive centers (21 with Holocene
52 activity) form the broad Ecuadorian volcanic arc, which covers an area up to 130 km wide north of 2°S
53 latitude (Hall and Wood, 1985; Pedraza Garcia et al., 2007). Usually, these volcanoes are grouped
54 according to their distribution in along-arc alignments defined by their geographic relationship to the
55 two subparallel mountain ranges that form the Ecuadorian Andes (i.e., the Western and Eastern
56 Cordilleras), the tectonic depression that separates both ranges (i.e., the Inter-Andean Valley), and the
57 sub-Andean Amazonian lowlands (Fig. 1b; e.g., Hall and Beate, 1991; Hall et al., 2008; Ancellin et al.,
58 2017). Moreover, the distribution of volcanoes along the arc is not uniform. In fact, dozens of
59 independent edifices occur in areas of a few square kilometers, with distances between their summits
60 ranging from 6 to 12 km. These “volcanic clusters” alternate along the arc with areas with a small
61 number of volcanoes, which define the three distinct segments of the Ecuadorian arc: northern, central,
62 and southern (Fig., 1c).

63 Almost all of the Ecuadorian volcanic overlaps the in-land projection of notable subducting
64 structures of the Nazca Plate (Fig. 1a), such as the Grijalva Fracture Zone, and the Carnegie Ridge, the
65 latter created by the motion of the Nazca Plate over the Galápagos hotspot (Meschede and Barckhausen,
66 2001; Lonsdale, 2005; O'Connor et al., 2007). The presence of these oceanic structures, together with
67 the convex shape of the continental margin, has been interpreted to be responsible for the slab flexure
68 described beneath the Ecuadorian arc (Yepes et al., 2016; Portner et al., 2020). In addition, the oblique
69 convergence of the Nazca Plate is responsible for the motion of the northwestern margin of South
70 America, forming the North Andean Sliver (Witt et al., 2006; Alvarado et al., 2016). This displacement
71 occurs through the Chingual-Cosanga-Pallatanga-Puná (CCPP) fault system (Fig. 1c), which traverses
72 the Ecuadorian Andes and extends northward into Colombia (Witt and Bourgois, 2010; Nocquet et al.,
73 2014; Alvarado et al., 2016). Although several studies have been carried out on the slab structure (e.g.,
74 Gutscher et al., 1999; Michaud et al., 2009; Yepes et al., 2016) and the kinematics along crustal faults

75 (e.g., Fiorini and Tibaldi, 2012; Alvarado et al., 2014, 2016; Baize et al., 2020; Jomard et al., 2021),
76 their relationship with the volcanism is under discussion.

77 Volcanism in the central segment of the Ecuadorian arc occurs approximately between latitudes
78 0.1°S and 0.8°S , surrounding Quito, the capital of Ecuador. Twenty kilometers south of Quito, more
79 than a dozen of volcanoes stand in an area 70 km wide (E-W) and 40 km long (N-S) that defines the
80 central volcanic cluster of the Ecuadorian arc (Fig. 1c and 2). Although these volcanoes have been
81 studied individually and on a regional scale for geochemical and stratigraphic purposes (e.g., Chemin,
82 2004; Hidalgo et al., 2007; Hall and Mothes, 2008; Hall et al., 2017b; Ancellin et al., 2017; Chiaradia
83 et al., 2020; Santamaría et al., 2022), the geochronological data remain scarce and their eruptive
84 histories remain poorly studied (especially for the oldest edifices). In order to investigate the temporal
85 link between volcanism, tectonics and the geodynamic setting, we present here new geochronological
86 data together with new field observations for the volcanoes of the central segment of Ecuador, focusing
87 on its volcanic cluster. By combining the available ages, we describe for the first time the Pleistocene
88 eruptive history of this part of the Ecuadorian arc. Furthermore, this work aims to investigate the
89 relationship between ancient and recent tectonics and the development of volcanism in this area.

90

91 **2. GEOLOGICAL CONTEXT**

92 **2.1. Ecuadorian geological setting**

93 The Ecuadorian continental margin consists of a series of allochthonous and para-
94 autochthonous terrains containing several fault systems and sutures roughly parallel to the trench
95 (Cediel, 2019). The Oriente Foreland Basin (Fig. 1b) corresponds to a sedimentary sequence formed
96 since the Mesozoic that overlies the Precambrian Guyanese craton (Vallejo et al., 2021). The Eastern
97 Cordillera is formed by Paleozoic to Jurassic magmatic and metamorphic belts, whose protholites are
98 of both sedimentary and igneous origin (Litherland et al., 1994; Spikings et al., 2015). The Western
99 Cordillera consists of deformed Cretaceous mafic and ultramafic rocks which are overlain by sequences
100 of marine sediments and volcanic deposits (Vallejo et al., 2019). Further west, the Coastal Forearc

101 consists of several Mesozoic to Cenozoic sedimentary basins that were formed over an ultramafic
102 basement (Luzieux et al., 2006; Witt et al., 2006; Vallejo et al., 2019). These oceanic terrains are
103 interpreted as the remnants of an oceanic plateau accreted to the continental margin during the Late
104 Cretaceous-Paleogene (Spikings et al., 2010; Vallejo et al., 2019; Jaillard, 2022). The Pujilí suture (Fig.
105 1c) was formed after this accretionary event. The transition between the terrains of the Western and
106 Eastern Cordilleras is masked by the Inter-Andean Valley, an intramountain basin containing a thick
107 sequence of Miocene-Pliocene volcanoclastic sediments overlying a tectonic *mélange* composed of
108 continental and oceanic units (e.g., Aspden et al., 1995; Hungerbühler et al., 2002; Lavenu et al., 1995;
109 Winkler et al., 2005). The Quaternary volcanic arc overlies the Miocene-Pliocene volcanoclastic
110 deposits found in both Cordilleras and in the Inter-Andean Valley. In particular, the volcanoes of the
111 central segment were built on the sedimentary Silante (Late Oligocene-Middle Miocene) and
112 volcanoclastic Zumbahua (Middle Miocene) formations in the Western Cordillera (Vallejo et al., 2019,
113 2020), and the Pisayambo volcanics (Miocene) in the Eastern Cordillera (Barberi et al., 1988; Lavenu
114 et al., 1995; Egüez et al., 2017).

115

116 **2.2. Volcanism in the central volcanic cluster of the Ecuadorian Andes**

117 The central segment of the Ecuadorian volcanic arc occurs roughly between latitudes 0.1°S and
118 0.8°S (Fig. 1c). Although this distinction primarily includes volcanoes such as Pichincha (Robin et al.,
119 2010), the Chacana caldera (Hall and Mothes, 2008b) and the group of edifices located in the Sub-
120 Andean zone (e.g., Hoffer, 2008; Mothes and Hall, 2008; Salgado et al., 2021), the present study focuses
121 on the volcanic cluster located between the Eastern and Western Cordilleras at 0.4-0.8°S latitudes (Fig.
122 2). Our study not only includes the volcanoes considered as active, but also those with confirmed or
123 estimated Quaternary activity. The geological background of these volcanoes is summarized below.

124 The **Almas Santas** volcano (3786 m asl; lat. 0°35'S; long. 78°51'W), located on the western
125 side of the Western Cordillera (Fig. 2), is one of the closest volcanic centers to the trench of the entire
126 Ecuadorian arc (~240 km). This volcano comprises a basal andesitic edifice built during a mostly

127 effusive stage followed by the emplacement of dacitic to rhyolitic lava domes, such as Cerro Azul, a
128 satellite lava dome located on the eastern flank of Almas Santas. A NW sector collapse partially
129 destroyed the volcanic edifice, probably at the end of its eruptive history (Chemin, 2004; Eissen et al.,
130 2005). No geochronological data are available for Almas Santas; a Middle Pleistocene age has been
131 suggested based on its highly eroded morphology (Chemin, 2004; Eissen et al., 2005).

132 To the east, four volcanoes are located on the eastern edge of the Western Cordillera, adjacent
133 to the Inter-Andean Valley (Fig. 2). La Carcacha edifice (3880 m asl; lat. 0°19'S; long. 78°36'W) is a
134 volcano dated at ~1.29 Ma (Hidalgo, 2006) associated with the **Atacazo-Ninahuilca volcanic complex**,
135 both located on the southern periphery of Quito. The Atacazo edifice (4455 m asl; lat. 0°21'S; long.
136 78°37'W), active between ~220 ka and ~83 ka (Hidalgo, 2006), partially covers La Carcacha edifice
137 and experienced a major sector collapse followed by the extrusion of several satellite lava domes around
138 70 ka (Hidalgo, 2006). At least six Plinian eruptions associated with the Ninahuilca dome complex,
139 formed within the sector collapse amphitheater of the Atacazo edifice, occurred during the Holocene
140 (Hidalgo et al., 2008). To the south, **Corazón** volcano (4784 m asl; lat. 0°32'S; long. 78°40'W) was
141 formed by andesite lava sequences and, like many other volcanic centers in the Western Cordillera,
142 exhibits a prominent sector collapse amphitheater opened to the west (Robles, 2013). A pyramidal peak
143 (glacial horn) created by the intense glacial erosion forms the summit of Corazón above 2800 m asl
144 (Fig. 2b). This structure consists of a thick sequence of monolithical breccias overlain by a sequence of
145 thin lavas. The satellite domes of Cerro Bomboli (with probable Holocene activity; Robles, 2013) and
146 La Moya are located on the northern and eastern flanks of Corazón volcano, respectively. Further south,
147 **Iliniza** volcano (5248 m asl; lat. 0°40'S; long. 78°43'W) is composed of two superimposed
148 stratovolcanoes active between ~124 and ~116 ka, and ~45 and ~25 ka, respectively. Iliniza volcano is
149 surrounded by the Pilingo (~353 ka) and Tishigcuchi (probably Holocene) domes (Hidalgo et al., 2007;
150 Santamaría et al., 2022). The Pongo lava flow (~6 ka) represents its most recent activity (Santamaría et
151 al., 2022).

152 Three highly eroded volcanoes are located in the Inter-Andean Valley (Fig. 2). East of Corazón,
153 the **Pasochoa** volcano (4199 m asl; lat. 0°28'S; long. 78°29'W) is made up of voluminous basaltic

154 andesite lava sequences. A groundmass $^{40}\text{Ar}/^{39}\text{Ar}$ age of 1.33 ± 0.30 Ma was obtained from a southwest
155 lava flow (Opdyke et al., 2006). To the south of Paschocha, the **Rumiñahui** volcano (4722 m asl; lat.
156 $0^{\circ}35'S$; long. $78^{\circ}30'W$) is formed by two lava sequences that differ in their andesitic composition of
157 mid- to high-potassium, respectively (Starr, 1984). Both volcanoes exhibit eroded collapse
158 amphitheatres on their western flanks. To the southwest, the **Santa Cruz** volcano (3978 m asl; lat.
159 $0^{\circ}39'S$; long. $78^{\circ}38'W$) is composed of andesitic lavas and dacitic domes dated at about 700 ka
160 (Santamaría et al., 2022). Recent data suggest a renewed activity between ~ 79 and ~ 60 ka, forming the
161 Loma Saquigua dome (Santamaría et al., 2022). Between the Rumiñahui and Santa Cruz volcanoes
162 stands the *Tiopullo plateau*, a topographic high (3500 m asl.) within the Inter-Andean Valley that
163 divides the Machachi-Guayllabamba basin to the north and the Latacunga basin to the south. The
164 Tiopullo plateau has an elongated NW-SE shape approximately 10 km wide and 5 km long, reaching
165 an elevation of 400 m above the Inter-Andean Valley. The plateau shows flanks slopes of less than 7° ,
166 with shallow fluvial incisions, and a flat summit with no significant uplifts. Tiopullo, as well as most
167 of the central segment, is covered by a thick sequence of tephra fall deposits associated with the
168 Cotopaxi volcano (Hall et al., 2017a), making sampling of Tiopullo rocks difficult in this area.

169 East of Paschocha, on the western edge on the Eastern Cordillera (Fig. 2), the **Sincholagua**
170 volcano (4873 m asl; lat. $0^{\circ}32'S$; long. $78^{\circ}22'W$) is an eroded edifice for which no geochronological or
171 geochemical data are available. Further south, **Cotopaxi** (5897 m asl; lat. $0^{\circ}41'S$; long. $78^{\circ}26'W$) is the
172 only volcano of this volcanic cluster whose Holocene activity has been thoroughly studied (Cotopaxi
173 II edifice; e.g., Mothes et al., 1998; Hall and Mothes, 2008; Pistolesi et al., 2013; Tsunematsu and
174 Bonadonna, 2015; Vezzoli et al., 2017; Sierra et al., 2019). Its eruptive history began with an ancient
175 rhyolitic volcanic center (Cotopaxi I - Barrancas stage), whose products are preserved on Cotopaxi's
176 present-day southern flank. The remnants of the Cotopaxi-I caldera are overlain by a sequence of
177 andesite lavas and breccias associated with the Morurco Edifice (Cotopaxi I - Morurco stage), located
178 to the south of the ancient caldera rim. A voluminous andesite lava sequence, that flowed ~ 40 km
179 northward from source through the Pita River valley, is associated with this stage (Hall and Mothes,
180 2008). The ages of the rhyolite and andesite sequences are not fully constrained. Two fission-track ages

181 of 0.56 ± 0.04 and 0.54 ± 0.05 Ma were obtained from biotite-rich obsidians by Bigazzi et al. (1997),
182 but unfortunately the sampling sites were not provided. The Cotopaxi-I series and the southern flank of
183 Sincholagua are covered by a thick ignimbrite deposit corresponding to the **Chalupas** caldera-forming
184 eruption that occurred southeast of Cotopaxi (lat. $0^{\circ}47'S$; long. $78^{\circ}20'W$). The Chalupas eruption, dated
185 at 216 ± 5 ka (Bablon et al., 2020b), was followed by the construction of the **Quilindaña** andesite
186 edifice (4876 m asl) dated at ~ 184 and ~ 169 ka (Hammersley, 2003; Córdova et al., 2020). Several
187 tephra fall deposits older than 43 ka represent its most recent dated activity (Córdova et al., 2020).
188 **Huañuña** (4197 m asl; lat. $0^{\circ}37'S$; long. $78^{\circ}14'W$) and **Chaupiloma** (also called Rio Valle; 4126 m
189 asl; lat. $0^{\circ}40'S$; long. $78^{\circ}16'W$) are rhyolitic domes located to the north of the Chalupas caldera. Based
190 on stratigraphic evidence, these volcanic centers have been assigned an Holocene age (Mothes and Hall,
191 2008; Hall et al., 2017b). Northeast of Sincholagua and Huañuña, the **Antisana** volcano (5758 m asl;
192 lat. $0^{\circ}29'S$; long. $78^{\circ}08'W$) consists of three successive andesite edifices constructed since ~ 400 ka
193 (Hall et al., 2017b), including the voluminous Cuyuja lava sequence dated at 0.21 ± 0.03 Ma
194 (groundmass $^{40}\text{Ar}/^{39}\text{Ar}$; Opdyke et al., 2006). Stratigraphic evidence suggests that the most recent
195 activity at Antisana may have occurred prior to 800 yr BP (Hall et al., 2017b).

196

197 **3. METHODS**

198 **3.1. Sampling strategy**

199 Field campaigns were conducted between 2016 and 2020 to identify and describe the main
200 volcanic units, to establish their stratigraphic relationships, and to collect fresh rock samples for K-Ar
201 and $^{40}\text{Ar}/^{39}\text{Ar}$ dating, and whole-rock geochemical analyses. A sledgehammer was used to sample inner
202 parts that were not exposed to ambient air and located away from the outer weathered crust. Due to the
203 scarce information on the stratigraphy of some of the volcanoes in the central cluster, we studied the
204 global structure of each edifice as explained below. In order to cover the maximum number of cone
205 building stages, we sampled, whenever possible, the units located at the summit, mid-altitude, and base

206 of the studied volcanoes. Considering the arrangement of the access routes, our sampling was performed
207 on several flanks of each volcano to ensure an adequate spatial and stratigraphic distribution of the data.

208 At Almas Santas volcano, one sample was recovered from the Tangan columnar jointed lava
209 flow (19EQ36), located in a lower section of its southern flank, near the Río Toachi canyon (Fig. 2a).
210 Based on its stratigraphic position, it corresponds to an early stage of Almas Santas. An additional
211 sample was collected from a metrical andesitic block found at the base of the Cerro Azul satellite cone,
212 on the eastern flank of Almas Santas (19EQ43). A total of thirteen samples were collected from Corazón
213 volcano. Samples 19EQ05, 19EQ07 and 19EQ10 correspond to massive lava flows that form the
214 southern and southwestern summit ridges of the volcano (Fig. 2b). These ridges were probably formed
215 in a late stage of Corazón's history, as they are relatively well preserved from erosion. In addition,
216 sample 19EQ11 was collected from the uppermost section of a lava sequence from the Quitasol river
217 canyon, located at the base of the Bomboli satellite cone (northern foothills of Corazón; Fig. 2a). Further
218 south, a massive lava flow exposed on the northern flank of Corazón was sampled (19EQ13). A juvenile
219 block was collected from a nearby pyroclastic density current (PDC) deposit (19EQ14a). Two samples
220 were taken from a sequence of tephra fall deposits exposed on the northern flank of Corazón (19EQ15a,
221 19EQ15b), probably corresponding to a recent activity at Cerro Bómboli. Finally, an andesitic block
222 was recovered from the monolithological breccias at the base of the pyramidal peak of Corazón
223 (19EQ09), as well as an interlayered lava flow (19EQ08). These breccias are overlain by a thick
224 sequence of thin lava flows (~1-5 m) that form the upper part of the summit. These lavas were sampled
225 at sites 20EQ83 and 20EQ84. Additionally, a dacite block was collected from an avalanche deposit on
226 the northwestern flank (20EQ50) near Atacazo-Ninahuilca volcano.

227 Eight samples were collected at Pasochoa volcano. Four lava flows were sampled from the
228 upper (19EQ31, 19EQ32, 19EQ33) and middle (19EQ34) sections of the radial ridges on the northern
229 flank of the volcano (Fig. 2). Sample 19EQ37 belongs to a lava flow found at the bottom of the Millipaso
230 ravine in the foothills of Pasochoa's southern flank. Samples 19EQ30 and 19EQ38 correspond to two
231 voluminous lava flows observed in the margins of the southeastern and southwestern flanks of the
232 volcano. The scarce exposure of massive lava flows in the summit area precluded sampling; instead,

233 we collected a sample (19EQ42b) for geochemical analysis from one of the numerous dykes that occur
234 between the uppermost monolithological breccias. Likewise, the summit outcrops of Rumiñahui
235 volcano consist mostly of weathered monolithological breccias and rare massive lava flows intersected
236 by several andesitic dikes, which is suggestive of a highly eroded ancient edifice. An andesitic block
237 was collected from a monolithological breccia exposed near the lower section of the central peak
238 (19EQ35). Samples 19EQ27 and 19EQ39 correspond to massive lava flows observed on the
239 southeastern and northwestern flanks, respectively, whose surface morphology is partially identifiable
240 nowadays. Sample 19EQ28 corresponds to an eroded lava flow observed on the southeast ridge of the
241 volcano, which underlies the 19EQ27 lava flow.

242 The scarcity of access roads and trails to Sincholagua, together with its eroded morphology and
243 thick cover of Holocene deposits (soils and tephra fall deposits), prevented adequate sampling of this
244 volcano. One sample was collected from a lava flow outcropping on the uppermost section of the
245 southwestern ridge (19EQ41) and another from a distal lava flow located on the northeastern flank
246 (20EQ86). Only sample 19EQ40 belongs to a lava flow from the basal section of the summit area.
247 Following the description of Hall et al. (2008), we collected five samples from the older stages of
248 Cotopaxi volcano. Sample 20EQ77 corresponds to a massive mica-rich obsidian flow (Cotopaxi I -
249 Barrancas stage) outcropping at the base of Morurco peak. Two massive lavas (20EQ76, 20EQ78) were
250 sampled from the overlying sequence composed of andesitic lava flows and monolithological breccias
251 (Cotopaxi I - Morurco stage) outcropping in the upper section of the Morurco river canyon. Finally,
252 two samples of the voluminous lava flow that filled the Pita River valley were collected in the Bocatoma
253 (19EQ29) and Tanipamba (20EQ88) areas.

254

255 **3.2. K-Ar dating**

256 Twenty unaltered samples from the central volcanic cluster were selected on the basis of
257 meticulous thin-section examinations (Appendix A) for K-Ar dating using the unspiked Cassinoli-
258 Gillot technique (Cassinoli and Gillot, 1982). This technique has also been applied to date young

259 volcanic rocks from the Ecuadorian volcanic arc (e.g., Bablon et al., 2018, 2019, 2020a; Santamaría et
260 al., 2022; Samaniego et al., 2022), as well as from other Andean volcanic arc segments (e.g., Germa et
261 al., 2010; Pallares et al., 2016, 2019; Grosse et al., 2018) and worldwide (e.g., Germa et al., 2011;
262 Hildenbrand et al., 2018; Dibacto et al., 2020). All analyses were performed on groundmass, except one
263 on plagioclase phenocrysts (19EQ27) and one on obsidian shards (20EQ77). Samples were manually
264 crushed with a steel mortar and sieved to the 63-80, 80-125, or 125-250 μm fraction sizes, according to
265 their phenocrysts-to-groundmass size ratio. Following a 15 min cleaning in an ultrasonic bath with a
266 10% HNO_3 solution, they were rinsed with de-ionized water. Magnetic and heavy liquids (bromofom)
267 separation methods were then used to extract the groundmass in a narrow density range, removing
268 phenocrysts potential carriers of excess $^{40}\text{Ar}^*$ and any undetected weathered fraction. The Cassagnol-
269 Gillot technique was preferentially applied to the groundmass as it is the latest phase assumed to
270 crystallize in equilibrium with the atmosphere, and thus would provide the most probable age of the
271 sample and the emplacement of volcanic deposits.

272 The Cassagnol-Gillot technique is suitable for the detection of minute amounts of radiogenic
273 argon ($^{40}\text{Ar}^*$) produced by the radioactive decay of ^{40}K , which may be diluted in ^{40}Ar derived from
274 atmospheric contamination. The difference in the $^{40}\text{Ar}/^{39}\text{Ar}$ ratios obtained from the sample and from
275 an air aliquot, measured under identical conditions using a 180° sector multi-collector mass
276 spectrometer, allows quantification of the $^{40}\text{Ar}^*$ content (%). The detection limit of the mass
277 spectrometer, close to 0.1% for $^{40}\text{Ar}^*$ (Quidelleur et al., 2001), allows dating volcanic products even of
278 Holocene age with a relatively small uncertainty (Gillot et al., 2006). The ^{40}Ar signal is regularly
279 calibrated with systematic measurements of the HD-B1 standard with an age of 24.18 ± 0.09 Ma
280 (Schwarz and Trieloff, 2007). The potassium (K) concentration was measured by flame absorption
281 spectroscopy, in conjunction with the standards MDO-G (Gillot et al., 1992) and BCR2 (Raczek et al.,
282 2001) for comparison and correction. Then, the $^{40}\text{K}/\text{K}$ ratio in nature and the ^{40}K decay constant (Steiger
283 and Jäger, 1977) allow the age of the sample to be calculated. Both potassium and argon measurements
284 were carried out at the GEOPS laboratory (Paris-Saclay University, France) and were performed at least
285 twice to verify their reproducibility within a $1-\sigma$ uncertainty range. For a full description of sample

286 preparation, analytical procedures, and age and uncertainty calculations, the reader is recommended to
287 see Bablon et al. (2018).

288

289 **3.3. $^{40}\text{Ar}/^{39}\text{Ar}$ dating**

290 For the sake of comparison with the K-Ar technique, groundmass aliquots of samples 19EQ07
291 and 20EQ84 from the Corazón volcano were also dated using the $^{40}\text{Ar}/^{39}\text{Ar}$ technique. This exercise
292 allows us to verify the accuracy of our dating and to highlight the presence or absence of external factors
293 such as alteration and isotopic fractionation that could disturb the K-Ar clock (cf. Schaen et al., 2020).
294 Both samples were irradiated for 60 min in the CLICIT facility of the TRIGA reactor at the Oregon
295 State University. The Alder-Creek Sanidine standard ACs-2 with an age of 1.189 Ma (Niespolo et al.,
296 2017) was used for neutron fluence determination. The complete experimental procedure is described
297 in detail in Guillou et al. (2011). Samples were loaded into a double-vacuum resistance furnace for mid-
298 temperature ($\sim 600^\circ\text{C}$) pre-degassing under pumping, followed by a nine-step incremental heating
299 experiment from approximately 700 to 1200°C . The extracted gases were purified using a Ti
300 sublimation pump and two GP-MK3 SAES Zr-Al getters operating at 400°C . Analyses of the five argon
301 isotopes were performed using a GV5400 instrument. Mass discrimination was calculated from
302 repeated analyses of air pipettes using an $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 298.56 (Lee et al., 2006). Interfering isotope
303 corrections, as well as other constants used are reported in Appendix B.

304

305 **3.4. Whole-rock geochemical analyses**

306 Whole-rock major and trace element contents were measured for all dated samples as well as
307 for the other 15 additional samples collected specifically for geochemical analyses, completing a dataset
308 of 35 new analyses. Agate-crushed powders were analyzed by Inductively Coupled Plasma-Atomic
309 Emission Spectrometry (ICP-AES), at the Geo-Ocean Laboratory, Université de Bretagne Occidentale
310 (Brest, France), following the analytical procedure described in Cotten et al. (1995). Relative
311 uncertainties are lower than 1% for SiO_2 , and 2% for the other major elements, and 5% for trace

312 elements. Major element concentrations were recalculated to a total of 100% on a water-free basis and
313 are presented in Appendix C.

314

315 **3.5. Numerical reconstructions of paleotopographies for volume calculations**

316 Numerical reconstructions of paleotopography provide a useful tool in the comprehension of
317 the size and shape reached by a volcanic edifice while eluding its erosional features (e.g., Grosse et al.,
318 2009, 2020, 2022; Lahitte et al., 2012; Germa et al., 2015; O'Hara and Karlstrom, 2023). Here, we
319 consider the numerical reconstructions as a first approximation of the bulk volume of material
320 accumulated by the volcanic edifice at the end of its construction stage, as well as the amount of material
321 removed since the end of the volcanic activity. For this purpose, we used a 4-m resolution digital
322 elevation model (DEM) developed by the Sigtierras program of the *Ministerio de Agricultura y*
323 *Ambiente de Ecuador* (www.sigtierras.gob.ec). The structural features were mapped using a slope map
324 obtained from this DEM, as well as field observations, Google Earth® satellite imagery and
325 orthophotography.

326 Due to the limited stratigraphic constraints of most of the volcanoes studied, we opted for a
327 simple procedure to reconstruct the volcanic edifices. Therefore, we followed the method described by
328 Germa et al. (2015), Bablon et al. (2018, 2020a), and Santamaria et al. (2022), which is summarized as
329 follows. The basal surface of each edifice S_{t0} was modeled using an ordinary kriging interpolation of
330 the ArcGIS® software, which follows the surrounding topography starting from the basal outline of the
331 edifice. We manually draw the basal outline of each volcanic edifice based on available geological
332 maps, slope breaks, curvature maps and satellite imagery. The Kriging interpolation used points of
333 known elevation within 1 km around the basal outline to get a better fit of the modeled S_{t0} surface. A
334 regular 100 m point cloud was extracted from the Sigtierras DEM for each volcanic edifice. Based on
335 previous results from other volcanoes in the region (Bablon et al., 2018, 2020a; Santamaria et al., 2022;
336 Samaniego et al., 2022), we chose a conical model with a circular base and a concave profile shape,
337 interpreted as the surface reached at the end of the construction stage S_{t1} . Such profile corresponds to

338 the exponential trend line obtained by plotting the elevation of the preserved points against their
339 distance from a vertical symmetry axis. This trend line was shifted to obtain the best fit. Points located
340 in highly eroded areas, such as deep glacial and fluvial valleys, were discarded for profile modeling.
341 Thus, the points preserved in crests or interfluves (*planèzes*) were interpreted as low erosion surfaces.
342 The surface uncertainty at each point $\sigma_{S_{tn-i}}$ is provided by the prediction standard error map resulting
343 from ordinary kriging. The present-day surface topography S_{t2} is interpreted as the result of the erosion
344 of the modeled cone S_{t1} after the quiescence period, including possible large sector collapses, thus
345 maximizing the eroded volume. The construction stage volume v_{CS} and the erosion stage volume v_{eS}
346 were calculated by integrating the elevation difference between $S_{t0} - S_{t1}$, and $S_{t1} - S_{t2}$ surfaces
347 multiplied by the pixel area, respectively. The volume uncertainty σ_v corresponds to the combination
348 of the elevation uncertainties of each point σ_{e-i} multiplied by the pixel area, where $\sigma_{e-i} =$
349 $\sqrt{\sigma_{S_{tn-i}}^2 + \sigma_{S_{tn+1-i}}^2}$.

350

351 4. RESULTS

352 4.1. K-Ar dating

353 Twenty new K-Ar ages are presented in Table 1 and shown in Figure 2. K contents range from
354 0.76 to 1.75 wt.% for groundmass, reaching a minimum of 0.51 wt.% in plagioclase and a maximum of
355 2.4 wt.% in obsidian fractions. Radiogenic argon contents range from 0.5% to 28.9%, with a maximum
356 of 47.7% for plagioclase.

357 Samples from the eastern and southern flanks of Almas Santas volcano yielded similar ages of
358 374 ± 7 ka (19EQ43) and 364 ± 7 ka (19EQ36), respectively. Considering the sampling bias favoring
359 the upper exposed sections of the edifice, this narrow age range probably represents the youngest cone-
360 building stage of the volcano.

361 Further east, the Corazón volcano exhibits a wider range of ages between 178 ± 32 and 67 ± 4
362 ka. Notably, sample 19EQ08, taken from the base of the pyramidal peak was dated at 178 ± 32 ka and

363 probably represents an older phase of the volcano. A second sample taken slightly higher (Fig. 2b) and
364 dated at 175 ± 30 ka (20EQ84) supports this result. However, we treat both ages with caution due to
365 their high atmospheric contamination and low radiogenic argon content, reflected in their large
366 uncertainty range. An age of 149 ± 6 ka was obtained for a dacite block (20EQ50) collected from a
367 debris avalanche deposit located at the base of the northeastern flank of Corazón volcano. Finally, the
368 ages obtained from the lavas with fresh morphologies at the top of the ridges sampled on the northern
369 and southern flanks define a consistent range between 95 ± 3 ka and 67 ± 4 ka, the latter age being the
370 youngest age obtained for this volcano.

371 In the Inter-Andean Valley, the five ages obtained for Pasochoa volcano exhibit a narrow range
372 between 472 ± 8 and 423 ± 20 ka (Table 1). This range includes the voluminous lava flow outcropping
373 in the Pita River valley (19EQ30), on the eastern flank of Pasochoa volcano, dated at 450 ± 7 ka. Further
374 south, the highly weathered state of the Rumiñahui volcanic products precluded groundmass analyses.
375 Therefore, we analyzed plagioclase phenocrysts recovered from the less weathered sample 19EQ27,
376 which yielded an age of 207 ± 9 ka. This sample corresponds to a massive porphyritic lava flow from
377 the eastern flank of the volcano, which belongs to the late volcanic stage characterized by high-K lavas
378 (Starr, 1984). Given the possible presence of inherited radiogenic argon in plagioclase crystals (e.g.,
379 Singer et al., 1998), this result should be considered as a maximum value for the eruption age.

380 Similar to Rumiñahui, the Sincholagua lavas show intense weathering in most outcrops.
381 However, a fresh lava sampled on the eastern flank (19EQ41) yielded a groundmass K-Ar age of 316
382 ± 6 ka. Regarding Cotopaxi-I volcano, the obsidian flow at the base of the Morurco peak yielded an age
383 of 537 ± 11 ka (20EQ77), which is the oldest value obtained in this study. Finally, a lava flow exposed
384 south of Morurco (20EQ78), and the voluminous Pita lava flows (20EQ88) yielded ages of 334 ± 5 ka
385 and 295 ± 10 ka, respectively.

386

387 4.2. $^{40}\text{Ar}/^{39}\text{Ar}$ dating

388 Plateau ages, isochron regressions and probability of fit were calculated using ArArCalc
389 (Koppers, 2002) following the criteria of Sharp and Renne (2005). An isochron includes the maximum
390 number of consecutive steps with a probability of fit ≥ 0.1 . It consists of at least three or more steps that
391 contain $\geq 60\%$ of the ^{39}Ar released and it defines a trapped $^{40}\text{Ar}/^{36}\text{Ar}$ ratio not statistically different from
392 298.56. Retained criteria for acceptable age plateau are: (1) it must have a minimum of 3 or more
393 consecutive steps that contain 60% or more of the ^{39}Ar released, (2) no resolvable slope at 1σ analytical
394 uncertainty, (3) no outliers or age trends within the initial and final steps.

395 The step-heating experiments conducted on these two samples allow the calculation of age
396 plateaus with 87.5% (sample 20EQ84) to 97.0% (sample 19EQ07) of total gas released (Fig.3,
397 Appendix B). This is evidence that the K-Ar clock of these samples is not disturbed and that the
398 calculated ages are reliable. Indeed, according to the lost on ignition (LOI) values (-0.09 and 0.64%,
399 Appendix C), both samples are considered unaltered but with a slightly higher value of LOI for sample
400 20EQ84. This would explain that its apparent age spectrum appears more scattered, with ages ranging
401 from 72 ± 41 to 170 ± 97 ka. Although two consecutive steps (5 and 6) are slightly discordant, we
402 calculated a plateau age of 115.1 ± 15.2 ka for sample 20EQ84. The inverse isochron age of $148.1 \pm$
403 48.3 ka appears to be poorly constrained due to the very high atmospheric contamination of this sample,
404 with radiogenic ^{40}Ar content below 3% for all steps. The experiment of sample 19EQ17 yielded a
405 relatively well constrained plateau age of 94.3 ± 4.9 ka and an inverse isochron age of 87.9 ± 11.9 ka.
406 There is no evidence of $^{40}\text{Ar}^*$ excess or mass fractionation, as the $^{40}\text{Ar}/^{36}\text{Ar}$ intercept values calculated
407 for the two inverse isochrons (Fig.3) are within uncertainties the current atmospheric value. Therefore,
408 the equivalent but more precise plateau ages will be used in our study.

409

410 **4.3. Construction and erosion volumes of the central volcanic cluster**

411 The numerical reconstructions allowed us to calculate the bulk volume of the volcanic edifices
412 within the central volcanic cluster, as well as the volume of the material removed by erosion. It should
413 be noted that the surface models used do not take into account the amount of material lost during the
414 construction stages due to erosion or possible sectoral collapses, nor do they take into account far-

415 reaching products such as tephra fall deposits. Therefore, the edifice volumes obtained here
416 (construction and present-day volumes) are considered as minimum values, while the erosion volumes
417 are considered as maximum solely for their last quiescence period. On the other hand, the heterogeneity
418 of the volcanic materials prevents us from expressing our values as dense rock equivalent (DRE)
419 volumes, and therefore they are reported as bulk volumes. The calculated volumes are presented in
420 Table 2, together with previous volume estimates published for other volcanic centers. Our calculations
421 show that the most voluminous edifice (reconstructed volume) is the Almas Santas volcano with a bulk
422 value of $90 \pm 14 \text{ km}^3$, while the smallest is La Carcacha volcano with a value of $8 \pm 1 \text{ km}^3$. The average
423 volume reached by the volcanoes of the central volcanic cluster is $43 \pm 12 \text{ km}^3$, with Almas Santas
424 being the largest ($90 \pm 14 \text{ km}^3$) and Carcacha the smallest ($8 \pm 1 \text{ km}^3$). The present-day volumes of the
425 studied edifices range from $5 \pm 1 \text{ km}^3$ (Carcacha volcano) to $44 \pm 5 \text{ km}^3$ (Pasochoa volcano), with an
426 average value of 20 km^3 . The minimum uncertainty in the volumetric calculations is 10 vol.%, with a
427 maximum of 24 vol.%. The calculated volumes for volcanoes located in areas with irregular relief, such
428 as Almas Santas and Corazón ($\sigma_v > 7 \text{ km}^3$), show larger uncertainties compared to volcanoes located
429 in more regular or better-defined areas, such as Pasochoa or Cotopaxi ($\sigma_v < 6 \text{ km}^3$). Likewise, basement
430 surface roughness in mountain areas may underestimate or overestimate the volumes of volcanoes such
431 as Corazón or Almas Santas, respectively, due to the possible presence of ridges or hills in these regions.
432 The present-day volume of eroded material is of at least 24% of the initial volume. Notably, the Almas
433 Santas, Corazón and Sincholagua volcanoes exhibit the highest erosion percentages, up to 74 vol.% of
434 the pre-erosion volume. Furthermore, the Santa Cruz volcano, partially covered by recent volcanic
435 structures and edifices, presents considerable difficulties in estimating the volume preserved nowadays,
436 thus preventing the calculation of the eroded volume.

437 Note that output and erosion rates have not been investigated here, given the multiplicity of
438 factors that control these processes, and which are beyond the scope of this research. For instance,
439 factors such as the heterogeneity of the constituent eruptive products in a volcanic edifice, their
440 distribution around the main vent, and their mechanical resistance to erosion could cause noticeable
441 discrepancies in the volume achieved at the end of the construction periods (e.g., Hora et al., 2007;

442 Zernack et al., 2009; Yamamoto et al., 2018). On the other hand, external factors may influence the rate
443 of syn-eruptive erosion, which in turn biases the output rates. Examples of such factors include the
444 elevation of the edifice and the geographic setting, which influence the precipitation range and/or the
445 extent of glacial cover to which volcanic edifices are exposed through (Brook et al., 2011; Conway et
446 al., 2016; Pure et al., 2020; O'Hara and Karlstrom, 2023). At the same time, tectonic activity can
447 influence both the geometry of the volcanic edifice cone and its degree of degradation (Lagmay et al.,
448 2000; Mathieu et al., 2011; Mathieu and van Wyk de Vries, 2011). Additionally, output and erosion
449 rates are strongly influenced by the degree of knowledge of the eruptive history of each edifice, the
450 dispersion of geochronological information and the uncertainty in radiometric ages (e.g., Bablon et al.,
451 2020a).

452

453 **4.4. Geochemical characterization**

454 As shown in Figure 4a, most of the samples from this study are classified as medium-K basaltic
455 andesites to dacites, with SiO₂ contents ranging from 53 wt.% to 64 wt.%. The Cotopaxi-I obsidian
456 (20EQ77) is the only rhyolite in the group with 74 wt.% SiO₂. The K₂O contents vary between 0.7 wt.%
457 and 2.7 wt.%. Notably, samples 19EQ37 and 19EQ39, collected from Rumiñahui volcano, lie in the
458 boundary between the medium and high-K calc-alkaline series (Fig. 4a). Our data are consistent with
459 previous studies carried out on the central volcanic cluster. For instance, the sampled lavas from Almas
460 Santos volcano (19EQ36, 19EQ43) fall within the field defined by Chemin (2004) and Eissen et al.
461 (2005). Likewise, the lavas and breccias from the Corazón volcano form a more constrained lower silica
462 andesite field compared to the one provided by Schiano et al. (2010), which is defined by samples
463 collected around Cerro Bómboli. The andesitic lavas of Paschoa are consistent with the field defined
464 by the same authors. Only two dacite lavas were found in both volcanoes: 19EQ14a and 19EQ33,
465 respectively. The samples collected from Rumiñahui volcano belong to the two sequences described by
466 Starr (1984), with samples 19EQ39 and the dated 19EQ27 belonging to the high-K series. Finally, the
467 Cotopaxi-I samples are consistent with available geochemical data (Bryant et al., 2006; Garrison et al.,
468 2006, 2011). In particular, the obsidian 20EQ77 shows silica and potassium contents similar to those

469 reported by Bellot-Gurlet et al. (2008), i.e., samples CTX45 and CTX 46 dated by Bigazzi et al. (1997).
470 Considering the analogous mineralogical composition described by these authors, we can argue that our
471 sample corresponds to the same obsidian flow. In addition, samples collected from the Cotopaxi-I
472 southern flank (20EQ76 and 20EQ78) are consistent with the Morurco andesitic series (Garrison et al.,
473 2006). Although the Pita lava flow (19EQ29, 20EQ88) exhibits a lower silica content, plotting close to
474 the field described by the Pasochoa and Rumiñahui lavas, the Cotopaxi-I samples plot along a single
475 trend. Note that the geochemical data available for Cotopaxi-I are scarce, and thus its compositional
476 field is poorly defined.

477 Overall, the central volcanic cluster exhibits across-arc geochemical variations similar to those
478 described in other areas of the Ecuadorian arc (e.g., Barragan et al., 1998; Bourdon et al., 2003; Hidalgo
479 et al., 2012; Ancellin et al., 2017; Bablon et al., 2019, 2020a). Chondrite-normalized Rare-Earth
480 Elements (REE) plots (Fig. 4b; Sun and McDonough, 1989) show weak fractionation patterns between
481 Light REE (LREE; La, Ce, Nd) and Heavy REE (HREE; Dy, Er, Yb), with no significant Eu anomaly.
482 Trace elements normalized to primitive mantle diagrams (Fig. 4c) show an overall enrichment of Large-
483 Ion Lithophile Elements (LILE; Rb, Ba, and K) and Sr, and depletion of Nb, P, and Ti. The Cotopaxi-I
484 obsidian (20EQ77) has the highest P and Ti negative anomalies. Samples from the volcanoes in the
485 Eastern Cordillera (e.g., Cotopaxi, Sincholagua) exhibit a slight REE enrichment compared to those
486 from the Inter-Andean Valley (e.g., Pasochoa, Rumiñahui), reaching stronger HREE depletions in the
487 Western Cordillera (e.g., Almas Santas, Corazón). Accordingly, most incompatible element contents
488 are higher (e.g., La, Ba, Rb, Sr, Nb) in the Eastern Cordillera volcanoes, i.e., with increasing distance
489 from the trench, while the ratios of fluid-mobile to fluid-immobile (e.g., Ba/Th, Ba/Nb) elements are
490 lower (e.g., Ba/Th vs La; Fig. 5). Variations in REE contents are also observed for each volcano. For
491 instance, the andesite lavas from Almas Santas (19EQ36, 19EQ43) show a slight HREE enrichment
492 compared to the rhyodacite-rhyolite series (Chemin, 2004; Eissen et al., 2005). Likewise, the high-K
493 andesites from Rumiñahui volcano (e.g., 19EQ27, 19EQ39) and the dacite sample 19EQ33 from
494 Pasochoa volcano show the highest LREE enrichments of the Inter-Andean Valley volcanoes. The Pita

495 River lavas (Cotopaxi I - Morurco stage) are geochemically distinct from the Pasochoa lavas due to
496 their higher contents of incompatible elements and lower fluid-mobile to fluid-immobile ratios (Fig. 5).

497 Overall, the geochemical evolution of the magmas in the central volcanic cluster is strongly
498 influenced by crustal differentiation processes (cf. recharge, assimilation and fractional crystallization),
499 as suggested by the negative correlation between the compatible elements and the SiO₂ contents (Fig.
500 D1 and D2, Appendix D), as well as by several petrogenetic models proposed for the volcanoes in the
501 area (Barragan et al., 1998; Bourdon et al., 2003; Bryant et al., 2006; Chiaradia et al., 2009; Hidalgo et
502 al., 2012; Ancellin et al., 2017). These models support fractionation of variable amounts of plagioclase,
503 pyroxene, amphibole, and olivine. However, the occurrence of certain lavas with strong Y and HREE
504 depletion reported for volcanoes such as Ilinizas, Almas Santas, and Cotopaxi, can be explained by
505 more complex petrogenetic processes leading to higher amphibole and/or garnet fractionation (cf.
506 Chemin, 2004; Garrison et al., 2006; Hidalgo et al., 2007). Furthermore, the higher fluid-mobile to
507 fluid-immobile ratios observed in volcanoes located closer to the trench (e.g., Almas Santas, Corazón,
508 Pasochoa) suggest a significant role of aqueous slab fluids or melts in the mantle wedge metasomatism
509 (Ancellin et al., 2017). In summary, the geochemical variation of the central volcanic cluster can be
510 explained both by changes in the subducting slab inputs that metasomatize the mantle wedge, and by
511 fractional crystallization, crustal assimilation and magma mixing (e.g., Garrison et al., 2006; Hidalgo
512 et al., 2007, 2012; Chiaradia et al., 2009, 2020; Schiano et al., 2010; Bellver-Baca et al., 2020).

513

514 **5. DISCUSSION**

515 **5.1. Comparison with previous geochronological data**

516 Overall, the new radiometric ages obtained in this study are consistent with others reported in
517 the central volcanic cluster. An unpublished ⁴⁰Ar/³⁹Ar age obtained at the Laboratoire Geoazur (Côte
518 d'Azur University, Nice, France) was obtained for the Corazón volcano (M. Fornari pers. com.). Hand-
519 picked groundmass fragments from the sample BOM-5, collected north of the Bomboli cone (Fig. 2b),
520 yielded a plateau age of 190 ± 10 ka, and a consistent inverse isochron age of 188 ± 10 ka. These values

521 are significantly older than our K-Ar age of 91 ± 10 ka obtained from a nearby lava flow (19EQ11).
522 Considering the lower stratigraphic position of the BOM-5 sampling site (Fig. 2b; Fig. D3, Appendix
523 D), the occurrence of two lava sequences of different ages is plausible. Indeed, the BOM-5 age falls
524 within the range obtained here for the early cone-building stage of Corazón volcano, dated at 175 ± 30
525 ka (20EQ84) and 178 ± 32 ka (19EQ08), while the 19EQ11 age is consistent with the late stage, which
526 occurred between 67 ± 4 ka (19EQ05) and 95 ± 3 ka (19EQ07). Nevertheless, the groundmass
527 separation method used in BOM-5 does not prevent the occurrence of phenocrysts or weathered phases,
528 which could have biased the resulting age. Unfortunately, the lack of detailed data, such as age spectrum
529 and isochron age, makes this age difficult to interpret and prevents us from further investigation.

530 Opdyke et al. (2006) obtained a $^{40}\text{Ar}/^{39}\text{Ar}$ plateau (three steps only) age of 1.33 ± 0.30 Ma for
531 a normal polarity lava flow (EC-47) sampled on the eastern flank of Pasochoa. The corresponding
532 isochron yielded an age of 1.93 ± 2.88 Ma with an initial $^{40}\text{Ar}/^{39}\text{Ar}$ ratio of 271 ± 116 , indicating high
533 atmospheric contamination. The low precision of this age precludes comparison with the geomagnetic
534 polarity timescale; nevertheless, we note that the geomagnetic field was dominantly reverse during the
535 Matuyama Chron (i.e., 2.58 to 0.77 Ma; Cohen and Gibbard, 2019). Here we provide a K-Ar age of 450
536 ± 7 ka obtained from a nearby lava flow (19EQ30) belonging to the same unit. Our age is in good
537 agreement not only with the normal polarity reported by Opdyke et al. (2006), but also with our new
538 ages for Pasochoa volcano, which range from 423 ± 10 ka to 472 ± 8 ka (Table 1).

539 Two obsidian blocks belonging to the Cotopaxi-I rhyolitic stage were previously dated at 540
540 ± 50 ka (CTX 46) and 560 ± 40 ka (CTX 45) using the obsidian fission-tracks (Bigazzi et al., 1997).
541 By applying the K-Ar method for dating an obsidian flow (20EQ77), we obtained a consistent and well-
542 defined age of 537 ± 11 ka. The geochemical and petrographic similarities observed between our
543 samples and those of Bigazzi et al. (1997), including the presence of biotite and scarce quartz, suggest
544 that we have successfully dated obsidian samples from the same sequence using two different
545 techniques. Note that biotite crystals were removed here during sample preparation process.

546

547 **5.2. Comparison between K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ ages from this study**

548 Two samples from Corazón volcano were dated here using two techniques, K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$,
549 showing contrasting results. This can be explained by the quality of the lava samples and their
550 atmospheric argon contamination. Sample 19EQ07 has a total-gas relatively high radiogenic ^{40}Ar
551 content (3.6-3.9%; Table 1), which allowed precise measurements. In fact, using K-Ar dating, which
552 has a detection limit of 0.1% (Quidelleur et al., 2001), we obtained an age of 95 ± 3 ka. This value is in
553 very good agreement with the $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 94.3 ± 4.9 ka obtained for this sample (Fig. 3).
554 On the other hand, sample 20EQ84 has a low total-gas radiogenic Ar content of only 0.6% (Table1),
555 resulting in a rather poorly constrained K-Ar age of 175 ± 30 ka. This age is compatible at the one-
556 sigma level with the $^{40}\text{Ar}/^{39}\text{Ar}$ inverse isochron age of 148 ± 48 ka, and at the two-sigma level with the
557 $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 115.1 ± 15.2 ka. This highlights the difficulty of dating groundmass separated
558 from andesitic lavas with high atmosphere contamination using the K-Ar or $^{40}\text{Ar}/^{39}\text{Ar}$ techniques. Note
559 that the K-Ar age of 178 ± 32 ka obtained for the nearby sample 19EQ08 (Fig. 2b), which is also highly
560 contaminated ($^{40}\text{Ar}^*$ lower than 0.6%), is very close to the K-Ar age of 175 ± 30 ka obtained for
561 20EQ84, and that the four individual analyses for these samples cluster between 175 and 181 ka despite
562 their large uncertainty (Table 1).

563 This comparison demonstrates that no systematic error has affected either of these dating
564 techniques, and that K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ ages are reliable when obtained for fresh rocks with relatively
565 high radiogenic yields, such as sample 19EQ07.

566

567 **5.3. Eruptive history of the central segment**

568 Based on our new K-Ar ages, stratigraphic and morphological data, and previous studies carried
569 out in the central segment volcanoes, we present the eruptive history for this area of the Ecuadorian arc
570 as follows (Fig. 6; Table 3).

571 The oldest eruptive activity appears to have occurred in the north of the central segment. Several
572 geochronological studies suggest that volcanoes such as Pichincha (Robin et al., 2010), Chacana

573 (Opdyke et al., 2006; Bellot-Gurlet et al., 2008), Cayambe (Samaniego et al., 2005) and Mojanda-Fuya
574 Fuya (Bablon et al., 2020a) were active prior to ~1 Ma. In the central volcanic cluster area, only the
575 Carcacha volcano (Atacazo-Ninahuilca complex; Western Cordillera), adjacent to the Pichincha
576 volcano, has lava flows dated at ~1.30 Ma (Hidalgo, 2006). After a period of apparent quiescence,
577 volcanic activity resumed southward, forming the Santa Cruz volcano in the Inter-Andean Valley at
578 about 702 ± 11 ka (Santamaría et al., 2022). From ~550 ka, the volcanic activity seems to have increased
579 in the central volcanic cluster (Fig. 6). The Cotopaxi-I caldera (Eastern Cordillera) showed large, highly
580 explosive eruptions and effusive activity of rhyolitic affinity dated at 537 ± 11 ka (20EQ77). Later, the
581 construction of the andesitic Pasochoa volcano occurred in the Inter-Andean Valley, which was already
582 active between 472 ± 8 ka (19EQ34) and 423 ± 10 ka (19EQ37). Massive dacite lava flows and PDC
583 deposits, corresponding to the pre-caldera Chalupas volcanic system, erupted in the Eastern Cordillera
584 around 459 ± 9 ka and 418 ± 10 ka (plagioclase $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages; Hammersley, 2003).

585 Eruptive activity throughout the central volcanic cluster occurred between ~400 and ~300 ka.
586 In the Western Cordillera, the onset of the Almas Santas volcano (dated at 374 ± 7 and 364 ± 7 ka) and
587 the extrusion of the Pilongo lava dome (353 ± 6 ka, Iliniza volcano; Santamaría et al., 2022) took place.
588 We also note that the oldest dated activity of the Antisana (from 378 ± 38 ka; Hall et al., 2017b),
589 Cotopaxi-I Morurco (around 334 ± 5 ka), and Sincholagua (around 312 ± 6 ka) volcanoes in the Eastern
590 Cordillera occurred during this period. Due to sampling bias, these ages may mostly correspond to the
591 intermediate or more recent eruptive stages of these volcanoes. We propose that the emplacement of an
592 older edifice of the Rumiñahui volcano occurred during this eruptive stage of the central volcanic
593 cluster, or earlier, as suggested by (1) the widespread exposure of the dyke network in the summit area,
594 which implies a much higher degree of erosion compared to other edifices in the area, and thus a longer-
595 term erosional phase; (2) the upper bound provided by the 207 ± 9 ka age (19EQ27), which belongs to
596 the high-K andesite series defined by Starr (1984); and (3) the required presence of a prominent edifice
597 at the site of Rumiñahui volcano to channel the Pita lava flows (295 ± 10 ka) northward from the
598 Morurco cone (Cotopaxi-I volcano) to its terminus position east of Pasochoa volcano.

599 The apparent quiescence period in the Western Cordillera since ~300 ka ended when the
600 volcanic activity resumed south of Carcacha volcano, forming the basal edifice of Atacazo volcano.
601 This early cone was dated at ~200 ka (groundmass $^{40}\text{Ar}/^{39}\text{Ar}$ ages; Hidalgo, 2006). Further south, the
602 emplacement of the older Corazón series could have occurred at about 178 ± 32 ka (19EQ08). The
603 block (20EQ50) collected from an avalanche deposit outcropping between Corazón and Atacazo
604 volcanoes yielded a K-Ar age of 149 ± 6 ka. The Sr and Th contents compared to LILE (e.g., Ba) and
605 LREE (e.g., La) of this sample are consistent with those observed at Atacazo volcano (Fig. D4,
606 Appendix D), suggesting that this sample could be associated with Atacazo instead of Corazón. This
607 implies a possible extension of the Atacazo volcanic activity up to ~150 ka, providing an older bound
608 to its southwestern sector collapse.

609 In the Inter-Andean Valley, the activity resumed at Rumiñahui volcano around 207 ± 9 ka
610 (19EQ27), as suggested by the plagioclase K-Ar age obtained from its terminal andesitic series.
611 Nonetheless, since this age could be biased toward too old values by inherited argon (e.g., Singer et al.,
612 2008), it is possible that Rumiñahui volcano was active in more recent times. Synchronously in the
613 Eastern Cordillera, the voluminous Cuyuja lava flow (11 km^3) was erupted from a fissure located to the
614 southeast of Antisana volcano at 210 ± 30 ka (groundmass $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age; Opdyke et al., 2006;
615 Hall et al., 2017b). Further south, the Chalupas ignimbrite eruption (VEI 7) occurred southeast of
616 Cotopaxi-I volcano at 216 ± 5 ka (Bablon et al., 2020b), forming a ~17 km-wide caldera and a
617 widespread ignimbrite deposit that covered the Inter-Andean Valley (Mothes and Hall, 2008; Bablon
618 et al., 2020b). The early cone-building stages of Quilindaña volcano, an intra-caldera stratovolcano with
619 activity dated at 184 ± 3 ka (Buenavista dome; groundmass $^{40}\text{Ar}/^{39}\text{Ar}$ age; Córdova et al., 2020; Córdova
620 et al., 2020) and 169 ± 1 ka (plagioclase $^{40}\text{Ar}/^{39}\text{Ar}$ age; Hammersley, 2003), followed the Chalupas
621 eruption.

622 Finally, the volcanic activity appears to have been restricted to both cordilleras during the last
623 ~100 kyr. In the Western Cordillera, the Atacazo (Hidalgo, 2006) and Corazón volcanoes were active
624 until at least ~70 ka. Simultaneously, the construction of Iliniza volcano occurred to the south of the
625 Pilongo dome, beginning with its northern edifice at ~123-116 ka. It was followed by the onset of its

626 southern edifice at ~46-25 ka (Santamaría et al., 2022). The growth of the Loma Saquigua cone (79-60
627 ka) in Santa Cruz volcano is the only eruptive activity documented in the Inter-Andean Valley during
628 this period (Santamaría et al., 2022). Despite the lack of radiometric dates, the stratigraphic and
629 morphological evidence suggests that the Antisana volcano was also active during this interval (Hall et
630 al., 2017b). During the Holocene, the explosive activity of the Ninahuilca dome complex followed the
631 sector collapse of Atacazo volcano (Hidalgo et al., 2008), while the activity of Iliniza volcano was
632 mainly effusive (Santamaría et al., 2022). In the Eastern Cordillera, several explosive rhyolitic eruptions
633 preceded the construction of the andesitic cone of Cotopaxi II (Hall and Mothes, 2008). The fallout
634 stratigraphic relationships observed in the Eastern Cordillera suggest that the activity of the Huañuna
635 and Rio Valle rhyolitic centers apparently occurred during the Holocene (Mothes and Hall, 2008; Hall
636 et al., 2017b), as well as that of Antisana volcano and the Buenavista dome (Quilindaña volcano;
637 Córdova et al., 2020).

638

639 **5.4. Eruptive volumes**

640 Volumetric calculations indicate that the volcanoes in the central cluster grew to roughly similar
641 sizes (Table 2), reaching average bulk volumes of $43 \pm 12 \text{ km}^3$ (reconstructed volume). These volumes
642 provide a first-order estimate of the amount of erupted material, although factors such as the type,
643 distribution and bulk density of the volcanic deposits, as well as their syn-eruptive erosion, are not
644 accounted for. Tephra dispersion outside the volcanic edifice is an additional factor that is not
645 considered in our calculation. For instance, the bulk volume of fallout deposits of the Cotopaxi
646 Holocene ($< 4.5 \text{ ka}$) andesitic series is estimated to be between 4 and 9 km^3 (DRE volume ~ 1.5 to 3.5
647 km^3 ; Hall and Mothes, 2008), whereas the calculated bulk volume of the Cotopaxi edifice is $32 \pm 3 \text{ km}^3$.
648 We emphasize that all our calculated values should be considered as rough estimates, as more detailed
649 stratigraphic studies are required for each volcano. Figure 7b plots the accumulated bulk-volume of the
650 central volcanic cluster edifices over time. Due to its low density, the bulk volume of the Chalupas
651 ignimbrite of $230 \pm 30 \text{ km}^3$ (Bablon et al., 2020b) was replaced by its Dense Rock Equivalent (DRE)
652 of $\sim 100 \text{ km}^3$ (Hall and Mothes, 2008; Croweller et al., 2012) for comparison purposes only. Figure 7b

653 shows that the cumulative cone-building volume in the central volcanic cluster has been roughly stable
654 at a rate of $1.2 \pm 0.2 \text{ km}^3/\text{kyr}$ ($R^2 = 0.958$) since $\sim 550 \text{ ka}$. Thus, assuming that the cone-building
655 volumes are proportional to the erupted volumes, we suggest that the magmatic production has been
656 relatively constant for the central volcanic cluster during the last $\sim 0.5 \text{ Ma}$. This observation also seems
657 to apply to the clusters located in the northern and southern segments, according to data from Bablon
658 et al. (2019, 2020a) and references therein. Significant variations in growth or magmatic production
659 rates could have occurred throughout the eruptive history of each volcano, and thus, we strongly suggest
660 that this value should be taken with caution due to the calculation assumptions made.

661

662 **5.5. Temporal and spatial arrangement of the central segment volcanoes**

663 The most common volcanic landforms in the central segment are composite stratovolcanoes, lava
664 domes, and calderas which are distributed in NE-SW alignments following the morpho-structural units
665 of the Ecuadorian arc (Fig. 1 and 2). The position of Almas Santas volcano, located 15 km west of the
666 Volcanic Front, makes the central segment one of the widest in the Northern Andes. This location,
667 geographically closer to the trench, is also shared by Quilotoa, a 3 km-wide caldera located 30 km to
668 the south of Almas Santas. Notwithstanding this arrangement, the overall correlation between the
669 temporal evolution and geographic location of these volcanoes is puzzling, especially in the central
670 volcanic cluster. Indeed, Figures 6 and 7a show that although volcanic activity has been continuous in
671 each alignment for the last $\sim 550 \text{ ka}$, it was unevenly distributed. This observation contrasts with the
672 dynamics of the northern and southern segments, for which Bablon et al. (2019, 2020a) described a
673 relative migration to the northwest and south for the same period, respectively. Nevertheless, the
674 occurrence of edifices older than $\sim 1 \text{ Ma}$ to the north of the central segment (e.g., Viejo Cayambe,
675 Samaniego et al., 2005; La Carcacha, Hidalgo, 2006; Chacana Caldera, Opdyke et al., 2006; Ruco
676 Pichincha, Robin et al., 2010; Pre-Mojanda lavas, Bablon et al., 2020a) suggests an overall southward
677 extension of Ecuadorian volcanism in this area between roughly 1 Ma and 600 ka (Bablon et al., 2019).
678 From the above considerations, the central segment appears as a key area to better understand the

679 formation of the Ecuadorian arc and the factors that controlled the emplacement of volcanoes in this
680 area.

681 Evidence for the relationship between crustal architecture, and the position and timing of
682 volcanism is still scarce. Nevertheless, we offer a short discussion on this subject with possible issues
683 to be addressed in future research. As highlighted by Litherland and Aspden (1992), the distribution of
684 the Quaternary volcanoes in the Ecuadorian arc seems to be influenced by the major tectonic structures
685 of the continental crust (Fig. 8). In the central volcanic cluster, for instance, the Almas Santas volcano
686 and the Atacazo-Corazón-Iliniza volcanoes occur above ancient NE-SW oriented fault systems that
687 separate the Cretaceous oceanic units of the Western Cordillera (Hughes and Bermúdez, 1997; Hughes
688 and Pilatasig, 2002), e.g., the Pujilí fault. To the east, the tectonic structures of the Eastern Cordillera
689 are covered by thick Neogene volcanic sequences. Nevertheless, the position major structures such as
690 of the Peltetec fault, is inferred in our study area based on the change in slope of the western edge of
691 the Eastern Cordillera. This position coincides with the exposure of the Peltetec fault in the Chota
692 Valley to the north and in the Pisayambo area to the south (Litherland et al., 1994; Winkler et al., 2005).
693 The volcanoes of the Eastern Cordillera form NE-SW alignments that roughly coincide with the
694 orientation and position of these structures. The arrangement of the ancient structures of the Inter-
695 Andean Valley remains unclear due to the scarce basement exposures.

696 Regarding Quaternary tectonics, the central volcanic cluster is located in the interaction zone
697 between the Quito and Latacunga reverse fault systems, which are expressed to the north and south of
698 this area as parallel strands of folds over large major west dipping, blind, en-echelon thrust faults (Fig.
699 9; Fiorini and Tibaldi, 2012; Alvarado et al., 2014, 2016). These structures, which mainly affect the
700 volcano-sedimentary deposits on the eastern margin of the Inter-Andean Valley, seem to converge
701 towards the ancient Pujilí fault at deep (Western Cordillera; Alvarado et al., 2016) beneath the Iliniza
702 and Corazón volcanoes. The relationship of this fault system to volcanism is not clear. Nevertheless, a
703 progressive southward migration of volcanic activity appears to have occurred at the Iliniza volcano,
704 following the NE-SW axis consistent with the projection of the Pujilí suture (Santamaría et al., 2022),
705 while the preserved areas of the western flank of the Corazón volcano show NE-SW faults that possibly

706 contributed to its destabilization and sector collapse. Accordingly, Figure 9 illustrates that shallow
707 seismicity is present in this area of the Western Cordillera along the volcanic and tectonic structures
708 described above. Northeast of Iliniza, the Machachi right-lateral strike-slip fault is hypothesized to run
709 across the Inter-Andean Valley, extending along the NW flank of Rumiñahui volcano toward the SE of
710 Pasochoa volcano (Soulas et al., 1991; Egüez and Yepes, 1994). Although, we found no clear
711 morphological evidence for the Machachi fault trace, its orientation is compatible with the strike-slip
712 focal mechanisms observed south of Iliniza volcano (Pastocalle seismic zone; Basualto and Troncoso,
713 2003) and south of Pasochoa volcano (Pita Valley seismic zone; Hernández et al., 2020). The
714 occurrence of intense historical earthquakes in these zones (Beauval et al., 2010) suggests a potentially
715 higher degree of fault coupling. Furthermore, north of the Cotopaxi volcano, Fiorini and Tibaldi (2012)
716 described several minor strike-slip faults with NNE-SSW orientation in the Pita Valley. For these
717 authors, the Cotopaxi volcano zone acts as a fault transfer zone that accommodates the higher shortening
718 observed in the Latacunga basin compared to the Guayllabamba basin. Therefore, based on these
719 statements, we hypothesize the existence of a NE-SW system of active tectonic structures (albeit
720 blinded) between the Iliniza, Rumiñahui, Pasochoa, and Sincholagua volcanoes, rather than a single
721 failure. We recognize that the identification of active faulting is not straightforward in the central
722 segment due to the continuous cover of this area during the Holocene (mainly by tephra from the
723 Cotopaxi volcano). However, the above evidence suggests that Quaternary tectonics also played a
724 significant role in promoting magma ascent in this area.

725

726 **6. CONCLUSIONS**

727 The 22 new radiometric ages presented in this article provide the first geochronological data
728 for several edifices of the central volcanic cluster of the Ecuadorian Arc. Despite the significant erosion
729 experienced by some edifices, suggesting long-term exposures, most of them were constructed during
730 the Late Pleistocene. The earliest volcanic activity occurred between ~1.3 Ma and ~700 ka with the
731 onset of La Carcacha and Santa Cruz volcanoes (Hidalgo, 2006; Santamaría et al., 2022). From ~550
732 ka onwards, the volcanic activity in the region increased with the gradual formation of a “volcanic

733 cluster” composed of at least a dozen of stratovolcanoes and some smaller volcanic cones and lava
734 domes, spread over an area 70 km wide (E-W) and 40 km long (N-S). These volcanic features seem to
735 have been constructed probably over or near basement-inherited fault systems and sutures. Although
736 several Quaternary NE-SW fault systems have been described in this area (e.g., Soulas et al., 1991;
737 Egüez and Yepes, 1994; Alvarado, 2012; Fiorini and Tibaldi, 2012), the low deformation associated
738 with these systems suggests that they probably played a secondary, albeit important, role in the
739 development of the volcanoes arrangement, however, more research is needed on this topic. Although
740 the spatial development of volcanism in the central segment appears to be random in time, the
741 occurrence of older volcanoes in the north of this area is suggestive of a southward extension of
742 volcanism between ~1 Ma and ~550 ka. Numerical reconstructions show that the volcanic edifices from
743 the central cluster reached typical volumes on the order of $43 \pm 12 \text{ km}^3$. Based on the proposed
744 evolutionary history and our volumetric calculations, we infer that the overall volcanic output rate in
745 the region (and presumably the magmatic production rate) has been roughly stable at $1.2 \pm 0.2 \text{ km}^3/\text{kyr}$
746 during the last ~550 ka. However, we do not exclude the occurrence of sporadic magmatic pulses and
747 short periods of quiescence that could affect this rate over at shorter timescales.

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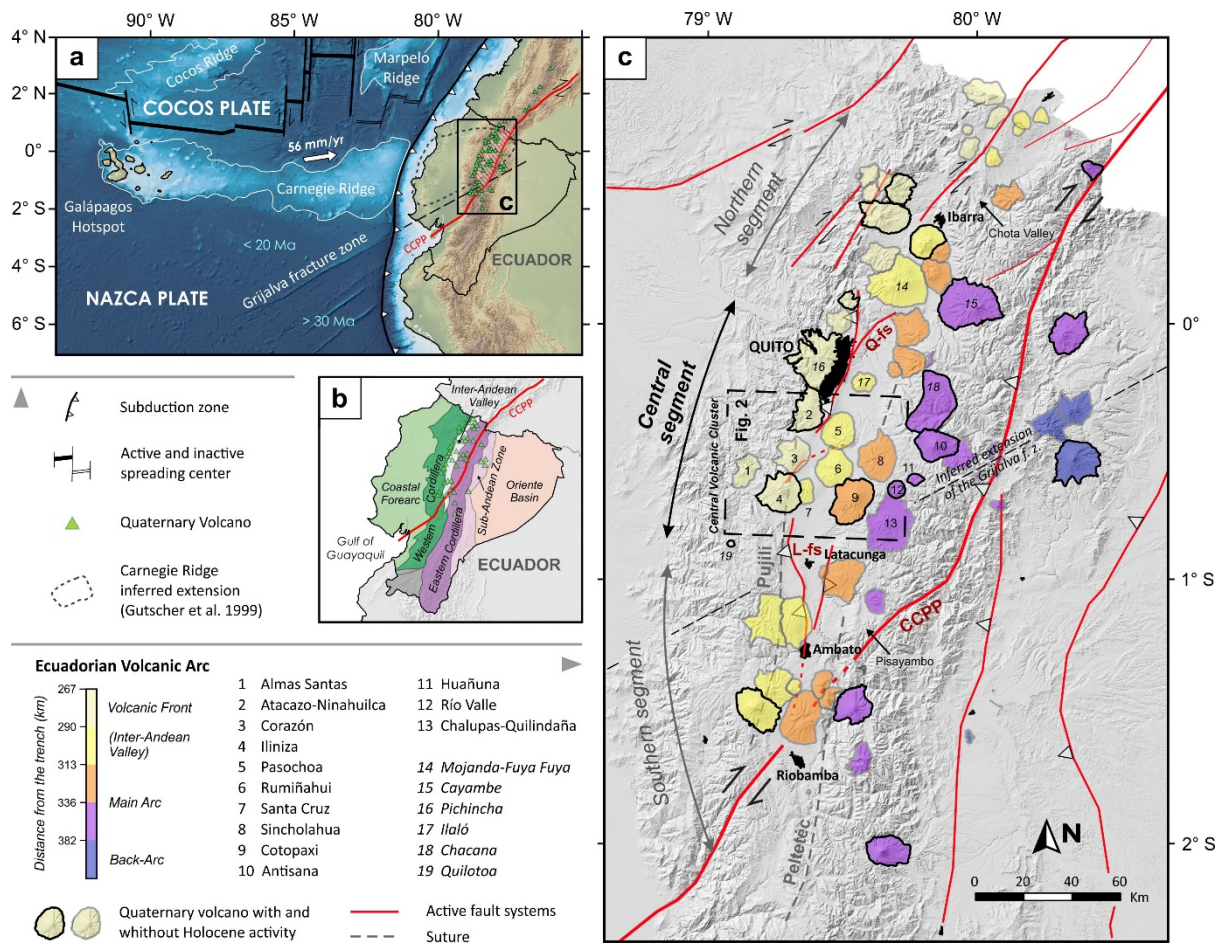
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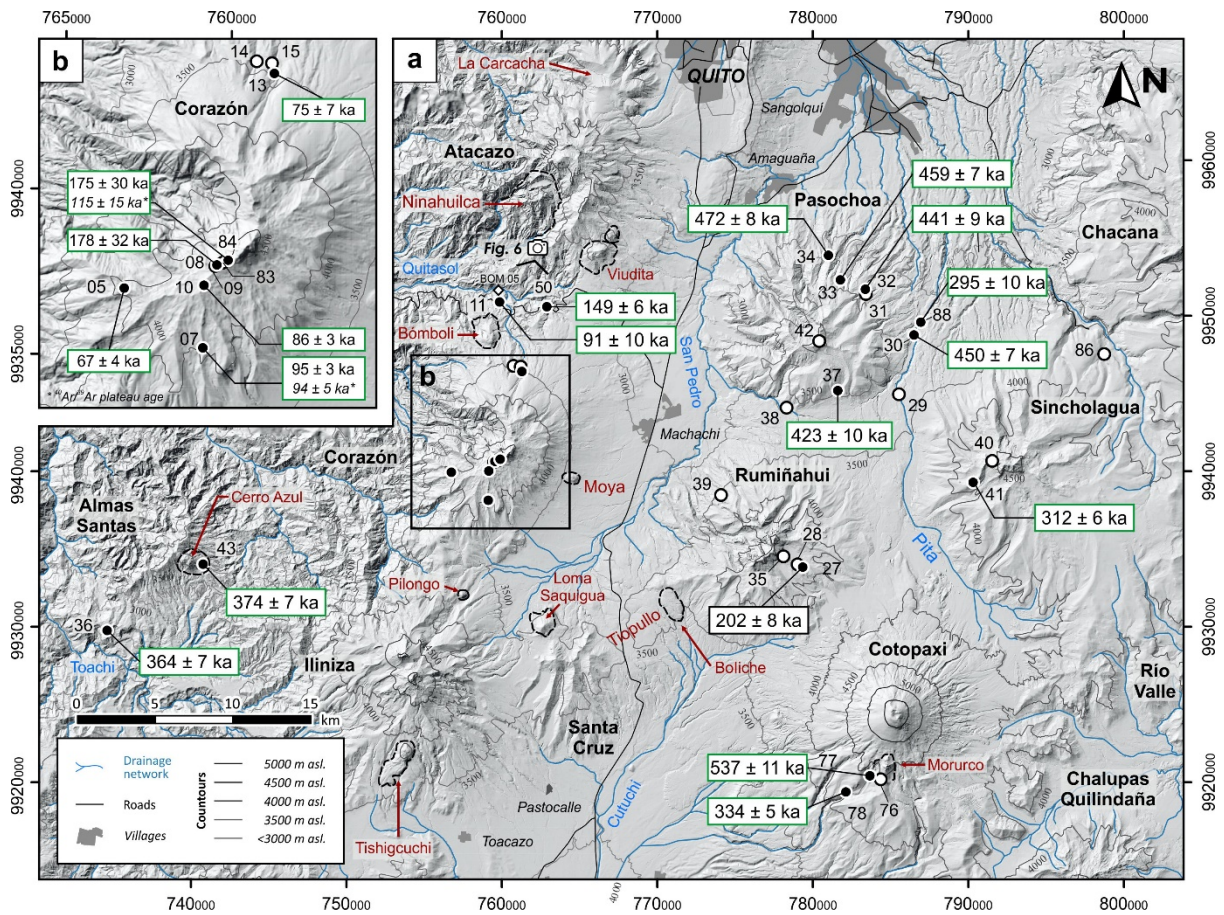
1179 **Figure captions**

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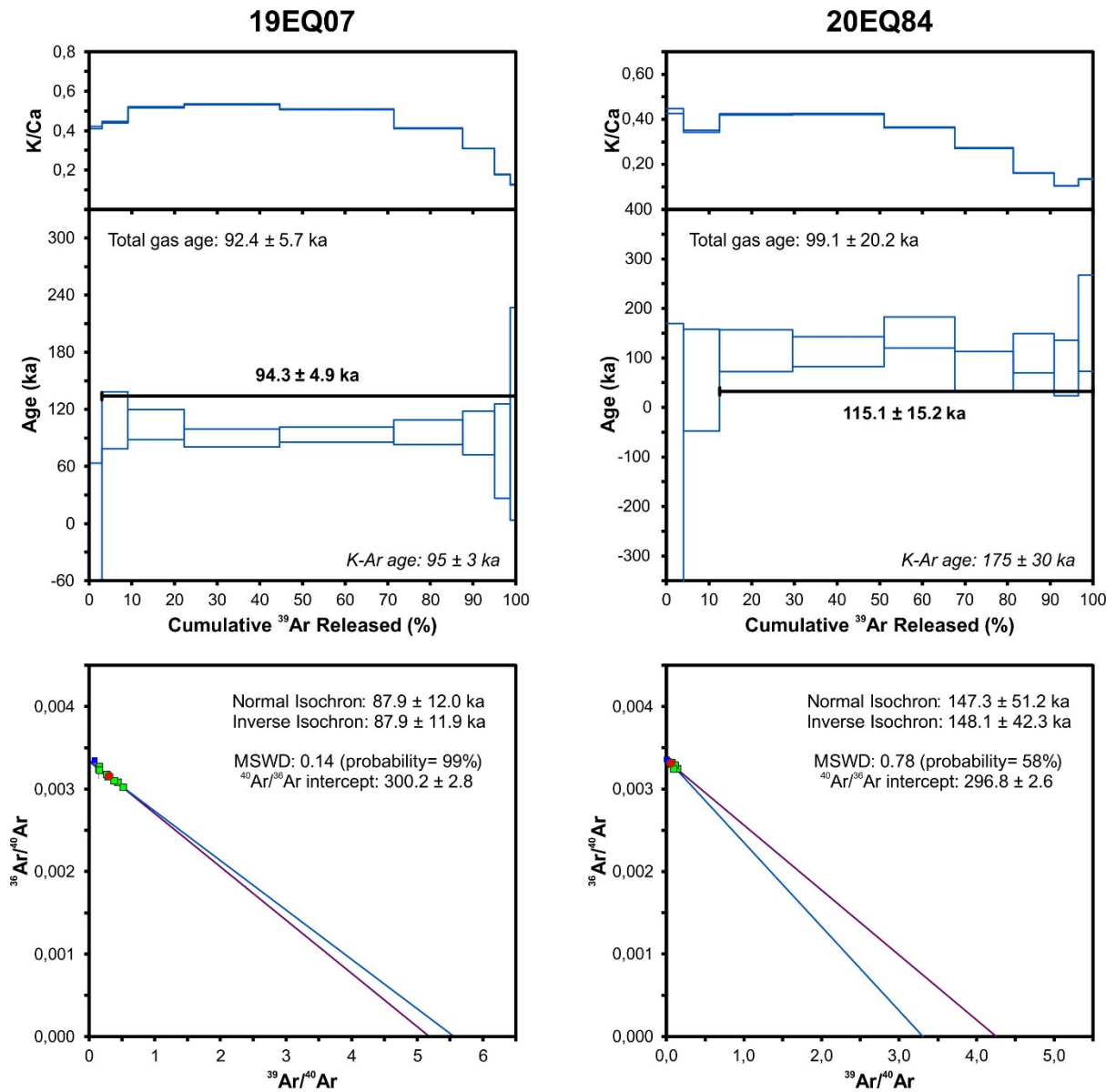


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1182 **Figure 1. a)** Regional geodynamic setting of the Ecuadorian margin. The white arrow indicates the
 1183 direction of motion of the Nazca plate relative to South America (DeMets et al., 2010). Topography
 1184 and bathymetry from the GEBCO 2020 program. **b)** Major geomorphologic provinces of Ecuador
 1185 (modified from Litherland and Aspden, 1992). **c)** Schematic map of the Ecuadorian volcanic arc
 1186 (modified from Bernard and Andrade, 2011). Volcanoes are colored according to their distance from
 1187 the trench, which includes the N-S alignments of the Volcanic Front (Western Cordillera), Inter-Andean
 1188 Valley, Main Arc (Eastern Cordillera), and Back-Arc. Variability in the number of volcanoes along-arc
 1189 is represented by the northern, central, and southern across-arc segments. Active fault systems are
 1190 represented by red lines according to Alvarado et al. (2016). CCPP: Chingual-Cosanga-Pallatanga-Puná
 1191 Fault System; Q-fs: Quito Fault System; L-fs: Latacunga Fault System. Suture zones are shown by grey
 1192 segmented lines. Major cities are shown in black.

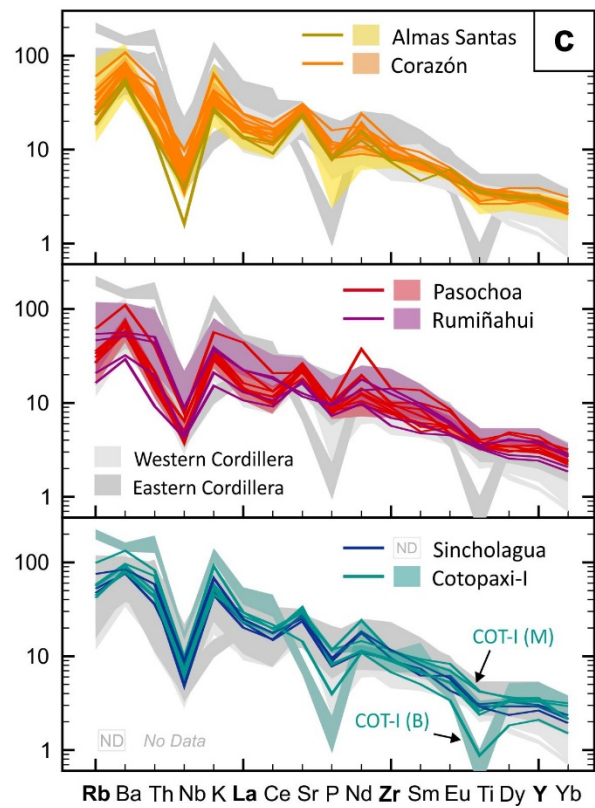
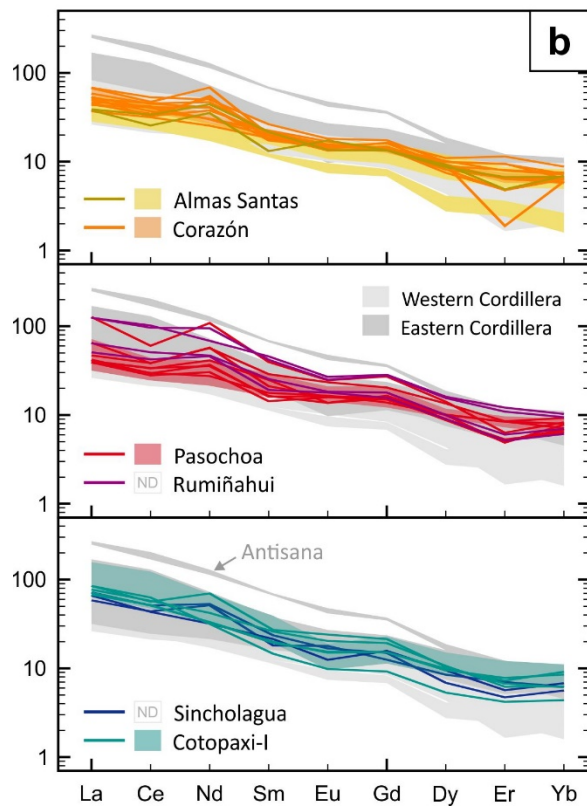
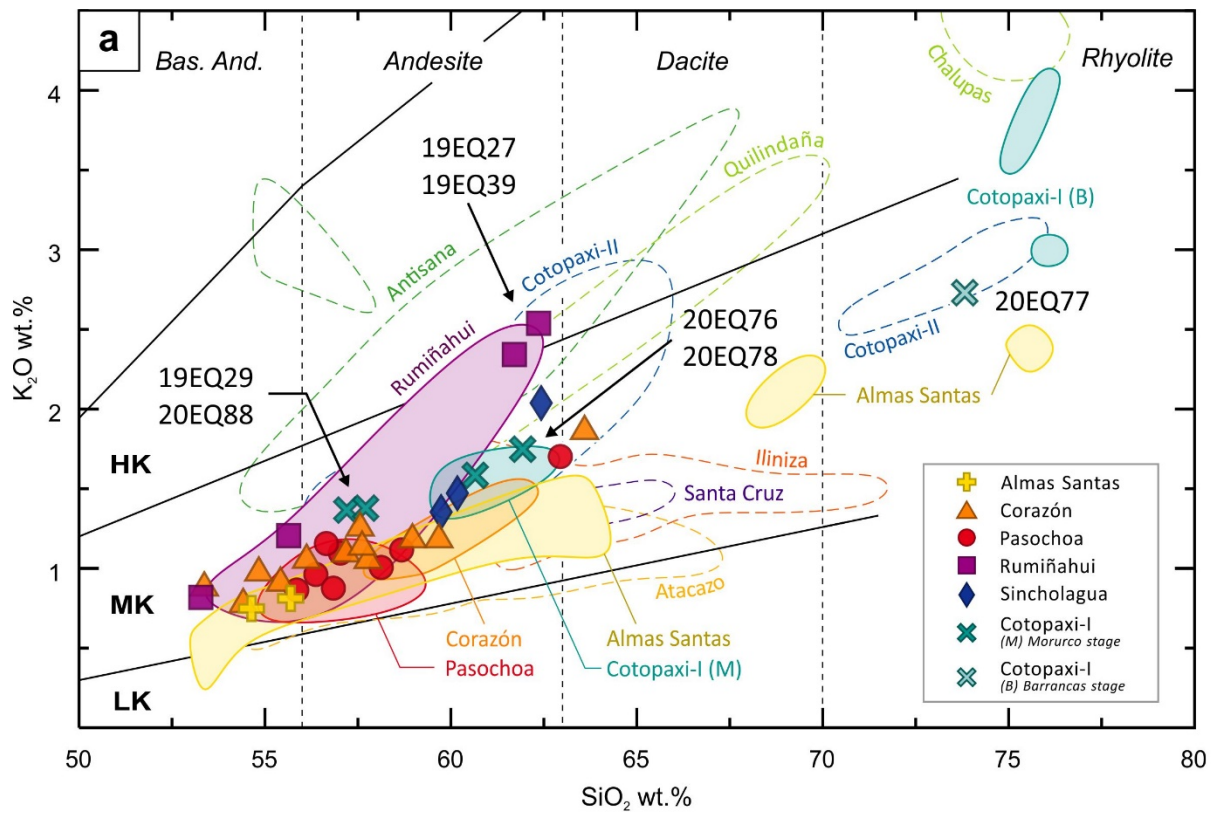


1195 **Figure 2. a)** Hill-shaded digital surface model (from the Sigtieras program) of the central volcanic
 1196 cluster of the Ecuadorian Arc showing the sampling locations and geochronological results. Numbers
 1197 correspond to the last two digits of the sample's names (19EQxx or 20EQxx, depending on the year of
 1198 recollection). K-Ar dated samples are shown as solid black dots. Volcanoes labelled in black. Satellite
 1199 lava domes and cones are denoted by dashed lines and are labeled with red letters. Rivers and valleys
 1200 names are labeled with blue letters. Coordinates are in Universal Transverse Mercator (UTM) zone 17.
 1201 **b)** Extended view of the Corazón summit area. ⁴⁰Ar/³⁹Ar plateau ages are shown in italic letters.



1202

1203 **Figure 3.** Results of $^{40}\text{Ar}/^{39}\text{Ar}$ analyses for samples 19EQ07 (left) and 20EQ84 (right). K/Ca ratio and
 1204 apparent age spectra (in ka) are shown below as a function of the cumulative ^{39}Ar content (in %), inverse
 1205 isochrons are shown below. Details are given in Appendix B.

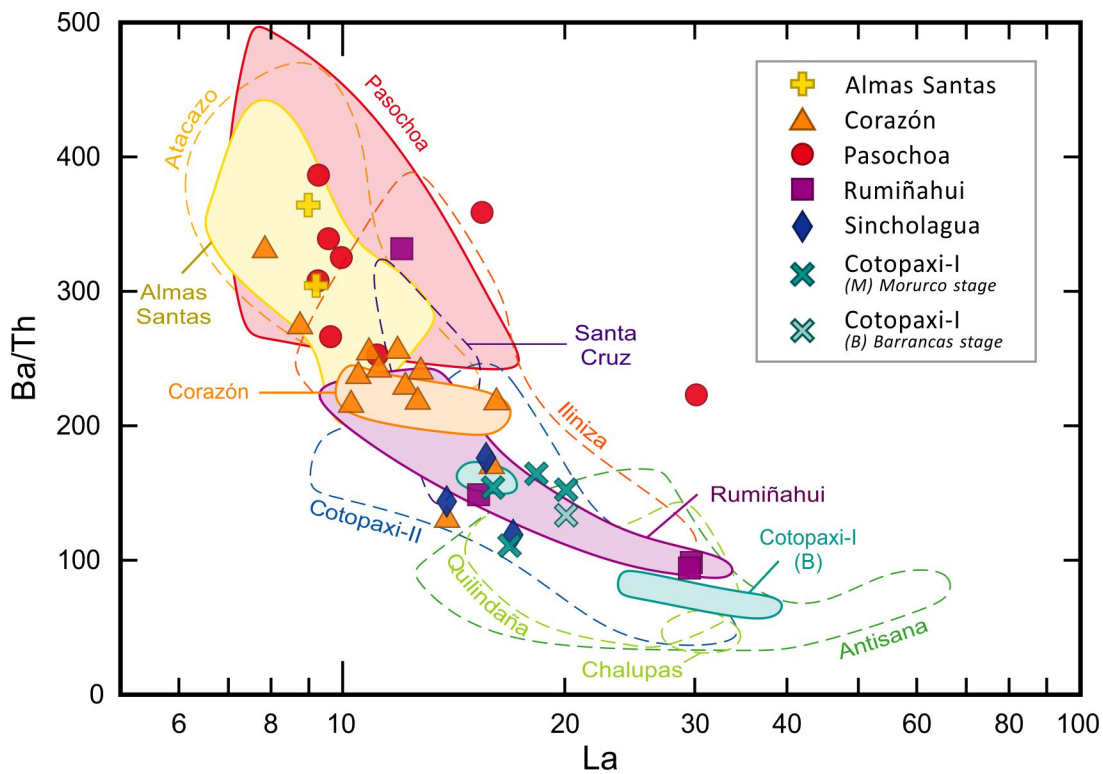


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1208 **Figure 4. a)** K₂O vs. SiO₂ diagram (Peccerillo and Taylor, 1976) for eruptive products of the central
 1209 volcanic cluster. HK: high-K, MK: medium-K, and LK: low-K calc-alkaline series. Data from this study
 1210 represented as point symbols. Shaded areas represent the compositional fields of volcanoes sampled in

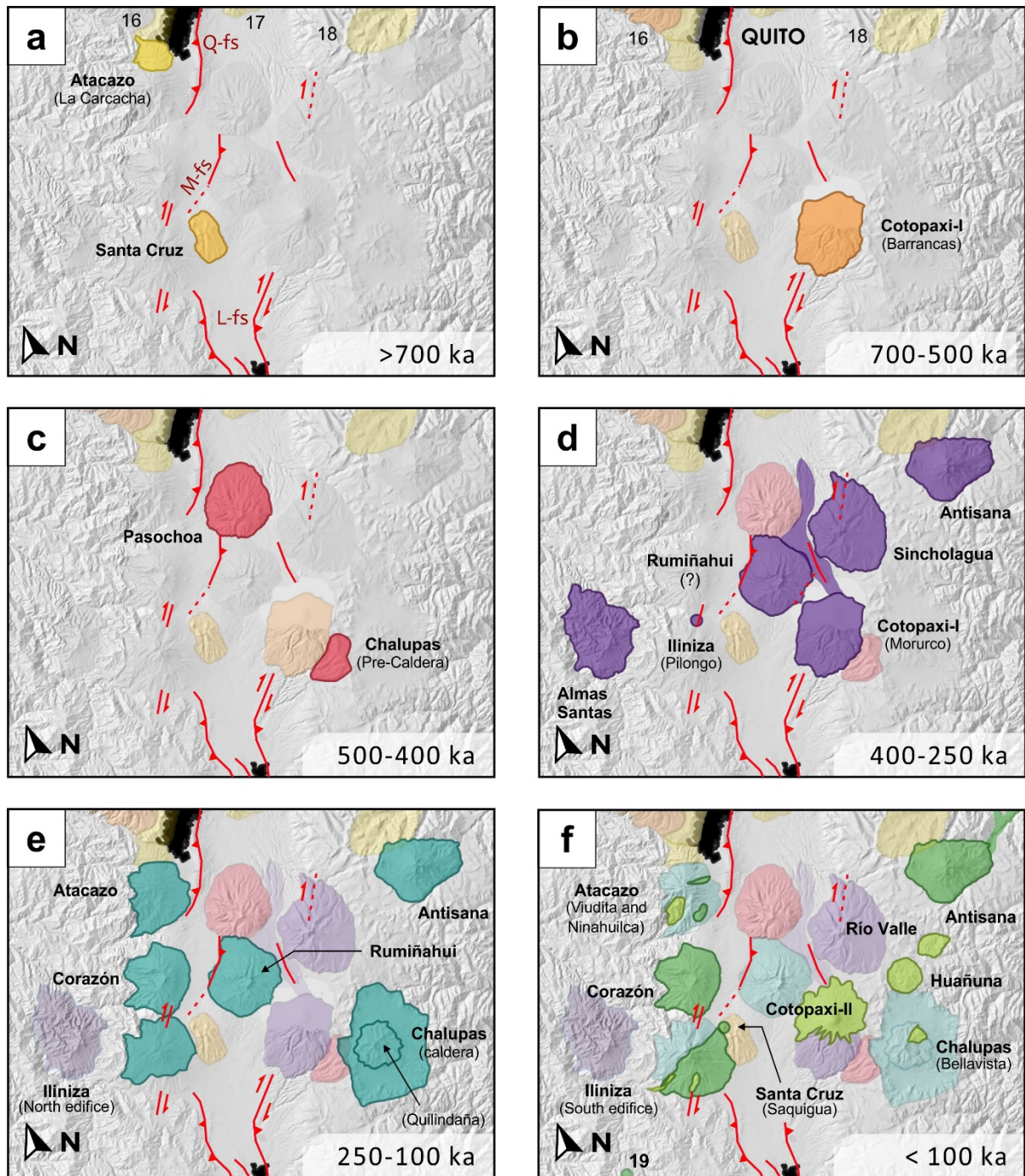
1211 this study while dashed areas are for other volcanoes, both areas with data taken from the Georoc
 1212 database and other studies (Starr, 1984; Chemin, 2004; Garrison et al., 2006; Bellot-Gurlet et al., 2008;
 1213 Schiano et al., 2010; Ancellin et al., 2017; Hall et al., 2017b; Bablon et al., 2020b; Chiaradia et al.,
 1214 2020; Córdova et al., 2020; Santamaría et al., 2022). **b)** Rare Earth Elements normalized to chondrites,
 1215 and **c)** Incompatible trace elements normalized to the primitive mantle diagrams (Sun and McDonough,
 1216 1989) for the same arrangements. The sampled volcanoes were organized according to their location in
 1217 the Western Cordillera (yellow and orange lines), the Inter-Andean Valley (red and purple lines), and
 1218 the Eastern Cordillera (blue and turquoise lines). The shaded areas represent the compositional fields
 1219 from bibliographic data; volcanoes with insufficient data are denoted as ND fields.

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1222 **Figure 5.** Ba/Th vs La diagram for eruptive products of the central volcanic cluster. Same data as Fig.
 1223 4a. Data from this study represented as point symbols. Shaded areas represent the compositional fields
 1224 of volcanoes sampled in this study while dashed areas are for other volcanoes, both areas with data
 1225 taken from the Georoc database and other studies (Starr, 1984; Chemin, 2004; Garrison et al., 2006;
 1226 Bellot-Gurlet et al., 2008; Schiano et al., 2010; Ancellin et al., 2017; Hall et al., 2017b; Bablon et al.,
 1227 2020b; Chiaradia et al., 2020; Córdova et al., 2020; Santamaría et al., 2022)



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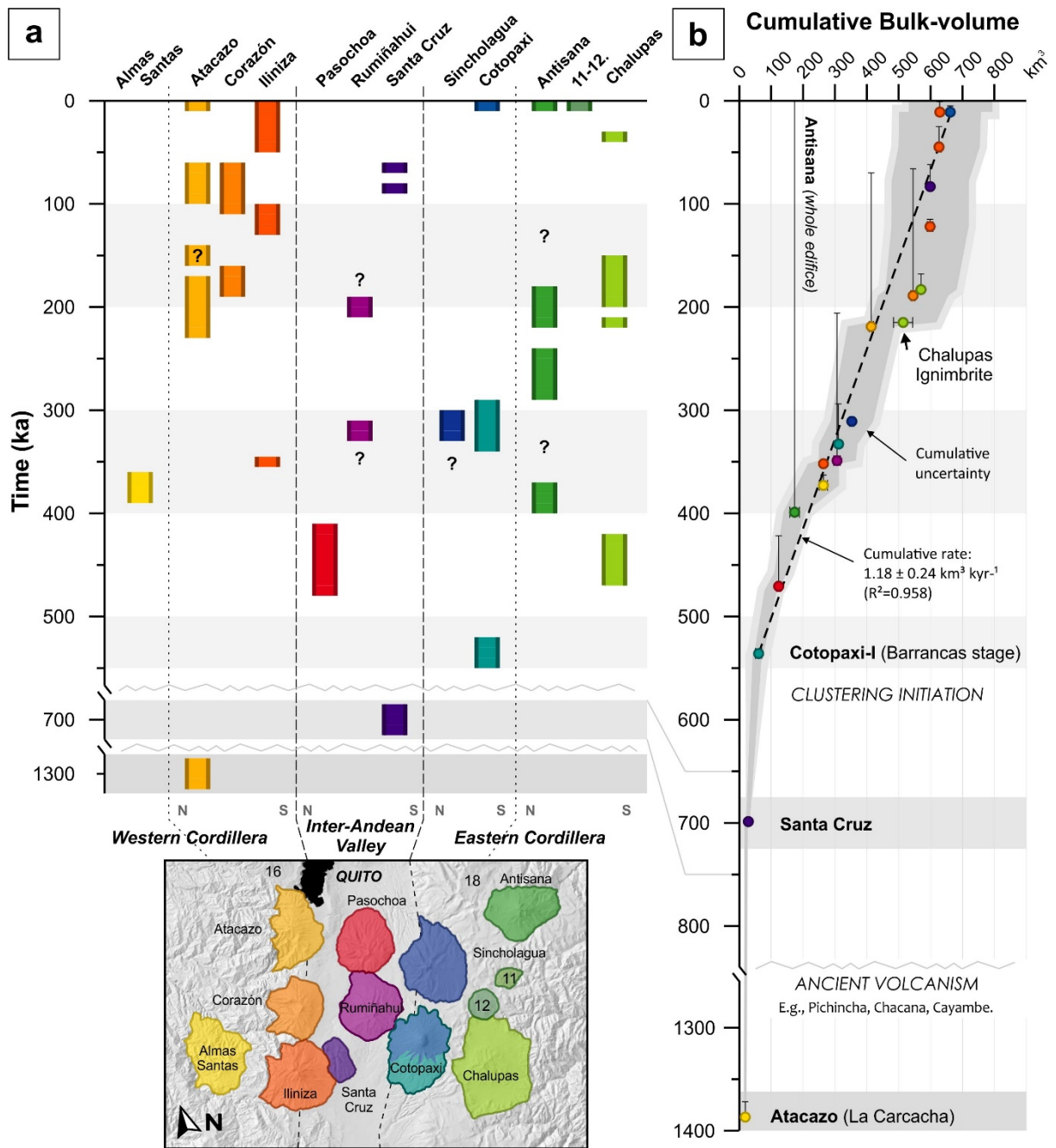
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Figure 6. Synthesis cartons of the eruptive history of the Ecuadorian central arc segment. **a)** Early stage of the Quaternary volcanic arc. Formation of the volcanoes Carcacha (1.3 Ma) and Santa Cruz (700 ka), as well as other contemporaneous edifices outside the study area: El Cinto (16), Ilaló (17), Chacana (18). **b)** Early construction of the volcanic cluster. Cotopaxi-I (Barrancas stage) at 550 ka. **c)** Pasochoa; Chalupas (pre-caldera deposits). **d)** Antisana-I; Almas Santas; Cotopaxi-I (Morurco stage); Pilongo lava dome of Iliniza; early stage of Rumiñahui; and Sincholagua. The distal flows of the Morurco cone are represented as a purple field north of Cotopaxi-I. **e)** Antisana; Atacazo; Chalupas caldera-forming eruption (216 ± 5 ka; Bablon et al., 2020b), and construction of the Quilindaña post-

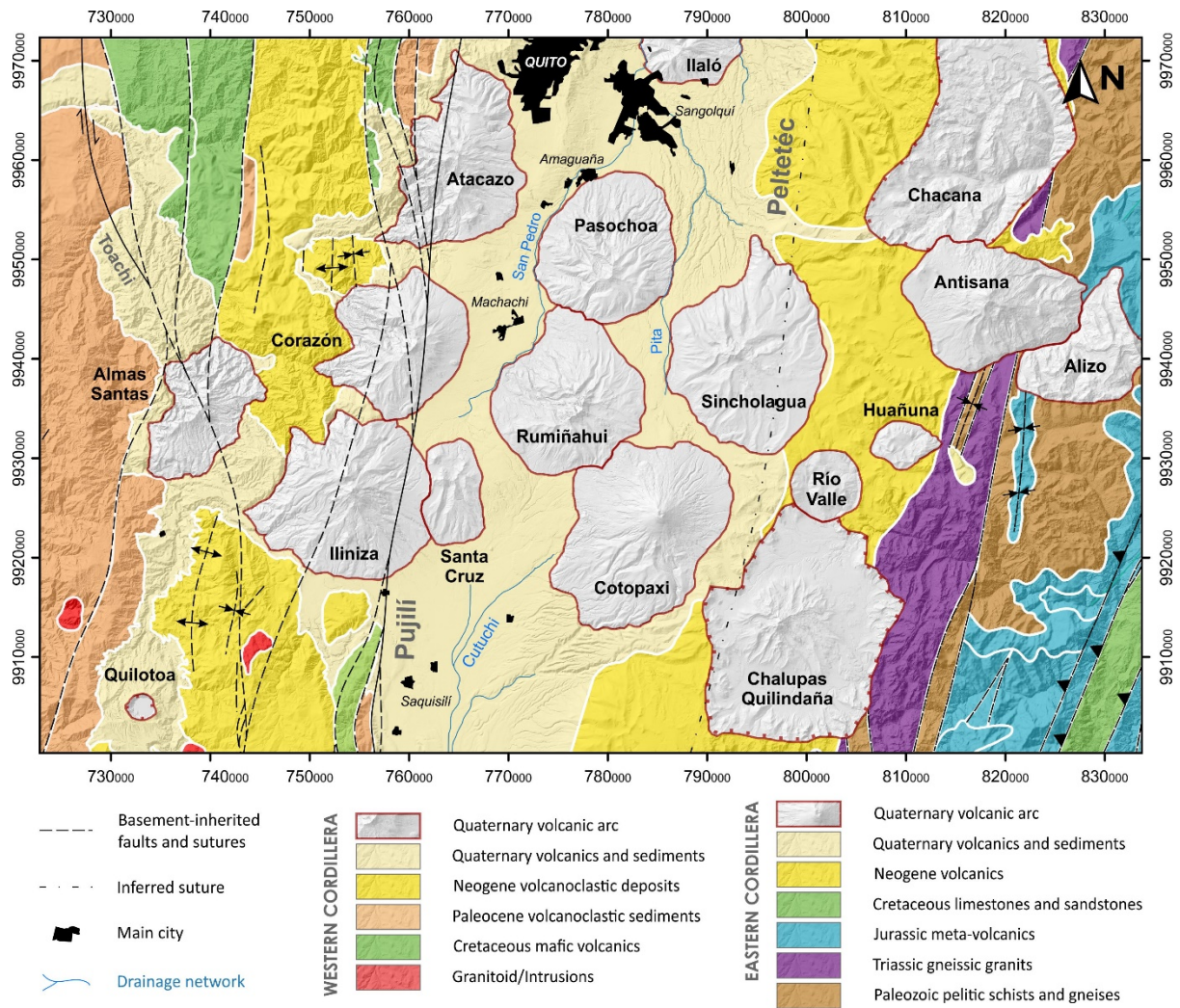
1237 caldera edifice; Corazón; North Iliniza edifice; late stage of Rumiñahui. **f)** Modern stage of the volcanic
1238 cluster (dark green) and its Holocene activity (light green). Antisana II and III; Atacazo satellite lava
1239 domes, and Ninahuilca lava dome complex; Corazón; Cotopaxi-II edifice; Bellavista lava dome;
1240 Huañuna lava dome; South Iliniza edifice, and its satellite lavas; Rio Valle lava dome; and Quilotoa
1241 caldera (19). Active fault systems are shown as red lines for all charts, according to Alvarado et al.
1242 (2016) and this study. Note that the maps are rotated slightly counterclockwise to match with the E-W
1243 orientation of the volcanic cluster. See text for full references.

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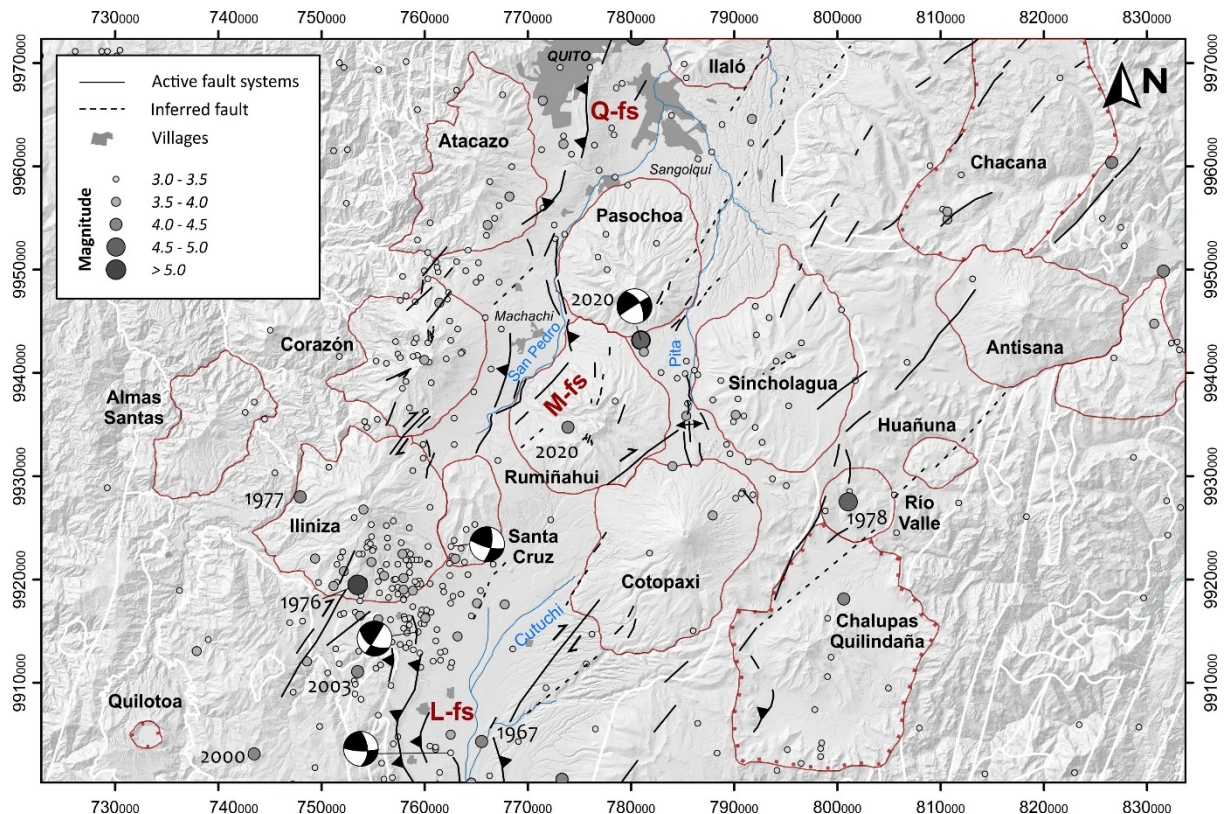
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1246 **Figure 7.** Temporal evolution of volcanism in the central segment of the Ecuadorian Arc. **a)** Schematic
 1247 representation of the individual cone-building stages through time. See text for details. **b)** Cumulative
 1248 bulk volume (km³) for the central volcanic cluster over time. Uncertainty bars indicate the extent of the
 1249 considered construction periods in ka according to Table 2. The bulk volumes of Antisana, Rumiñahui,
 1250 Corazón and Atacazo volcanoes do not distinguish the different cone-building stages due to the lack of
 1251 detailed stratigraphic data. The dashed line symbolizes the cumulative volume rate over the last ~550
 1252 ka, while the shaded area represents the cumulative volumetric uncertainty range. Volcano numbers as
 1253 in Figure 1.



1254

1255 **Figure 8.** Geologic map of the central segment basement (modified from Litherland et al., 1994; Hughes
 1256 and Bermúdez, 1997; Egüez et al., 2017; Vallejo et al., 2020). Dashed lines show tectonic structures
 1257 inherited from the basement. The Pujilí suture is drawn as a continuous line, and the inferred location
 1258 of the Pelteéc suture as a dotted line.



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Figure 9. Schematic map of the Quaternary fault systems of the central segment focused in the Inter-Andean Valley (Egüez and Yepes, 1994; Alvarado, 2012; Alvarado et al., 2014; Fiorini and Tibaldi, 2012; and this study). Q-fs: Quito fault-system; L-fs: Latacunga fault-system; M-fs: Machachi fault-system. Locations of the historical earthquakes according to the “Catalogo Homogenizado 1587 – 2011” of the IG-EPN, with hypocenter depths less than 40 km. The location of the AD 2020 earthquake according to Hernández et al. (2020). Moment tensor solutions from Basualto and Troncoso (2003) and Hernández et al. (2020).

1267

1268 **Tables**

1269 **Table 1.** K-Ar ages obtained in this study for central segment volcanoes. Column headings indicate
 1270 sample name, outcrop nature and relative location, sample coordinates projected using the Universal
 1271 Transverse Mercator (UTM) coordinate system (Zone 17), potassium (K) content in percent, radiogenic
 1272 argon ($^{40}\text{Ar}^*$) content in percent and in 10^{11} atoms per gram, age obtained for each measurement, and
 1273 weighted mean age in ka given with a $1-\sigma$ uncertainty. All measurements were performed on
 1274 groundmass, except for one sample measured on plagioclase phenocrysts (P) and one sample measured
 1275 on volcanic glass (G).

Sample	Location and Unit	UTM Easting	UTM Northing	K (%)	$^{40}\text{Ar}^*$ (%)	$^{40}\text{Ar}^*$ (10^{11} at/g)	Age $\pm 1 \sigma$ (ka)	Mean age (ka)
Almas Santos volcano								
19EQ43	Lava flow, Cerro Azul	740786	9934033	0.992	8.4%	3.8562	372 \pm 7	374 \pm 7
					8.1%	3.8998	377 \pm 7	
19EQ36	Lava flow, Tangan	734605	9929768	0.756	8.2%	2.8759	364 \pm 7	364 \pm 7
					7.4%	2.8822	365 \pm 7	
Corazón volcano								
19EQ08	Lava flow, pyramidal peak	759536	9940634	1.579	0.6%	2.9028	176 \pm 28	178 \pm 32
					0.5%	2.9836	181 \pm 38	
20EQ84	Lava flow, pyramidal peak	759883	9940775	0.972	0.6%	1.7824	176 \pm 30	175 \pm 30
					0.6%	1.7798	175 \pm 29	
19EQ07	Lava flow, S flank	759112	9938136	1.334	3.9%	1.3350	96 \pm 3	95 \pm 3
					3.6%	1.2996	93 \pm 3	
19EQ11	Lava flow, Cerro Bómboli	759847	9950892	1.323	0.9%	1.2223	88 \pm 10	91 \pm 10
					1.0%	1.3013	94 \pm 10	
19EQ10	Lava flow, S flank	759148	9940026	1.057	2.8%	0.9700	88 \pm 3	86 \pm 3
					2.7%	0.9196	83 \pm 3	
19EQ13	Lava flow, N flank	761280	9946424	1.279	1.1%	1.0225	77 \pm 7	75 \pm 7
					1.1%	0.9799	73 \pm 6	
19EQ05	Lava flow, SW flank	756746	9939943	0.966	2.0%	0.7031	70 \pm 4	67 \pm 4
					1.9%	0.6539	65 \pm 4	
Atacazo volcano								
20EQ50	Dacite block, S avalanche	762881	9950592	1.279	2.5%	1.9833	148 \pm 6	149 \pm 6
					2.8%	2.0019	150 \pm 6	

Sample	Location and Unit	UTM Easting	UTM Northing	K (%)	⁴⁰ Ar* (%)	⁴⁰ Ar* (10 ¹¹ at/g)	Age ± 1 σ (ka)	Mean age (ka)
Pasochoa volcano								
19EQ34	Lava flow, N flank	780987	9953901	0.856	12.0%	4.1969	469 ± 8	472 ± 8
					12.4%	4.2349	474 ± 8	
19EQ33	Lava flow, N flank	781758	9952313	1.807	26.5%	8.6492	458 ± 7	459 ± 7
					28.9%	8.6627	459 ± 7	
19EQ30	Lava flow, E flank	786494	9948763	1.080	11.5%	5.1295	455 ± 8	450 ± 7
					13.3%	5.0254	446 ± 7	
19EQ32	Lava flow, NW flank	783362	9951701	1.093	6.9%	5.0002	438 ± 9	441 ± 9
					7.1%	5.0665	444 ± 9	
19EQ37	Lava flow, S flank	781599	9945191	1.086	5.2%	4.7482	419 ± 10	423 ± 10
					5.1%	4.8376	427 ± 10	
Rumiñahui volcano								
19EQ27 ^P	Lava flow, E flank	779336	9933840	0.523	47.7%	1.0812	198 ± 8	202 ± 8
					43.4%	1.1254	206 ± 8	
Sincholagua volcano								
19EQ41	Lava flow, summit area	790298	9939301	1.739	9.0%	5.6975	314 ± 6	312 ± 6
					9.2%	5.6261	310 ± 6	
Cotopaxi volcano								
20EQ77 ^G	Obsidian flow, Morurco peak base	783660	9920417	2.430	6.2%	13.5144	532 ± 11	537 ± 11
					6.4%	13.7703	542 ± 11	
20EQ78	Lava flow, Morurco peak	782119	9919377	1.743	13.0%	6.1003	335 ± 5	334 ± 5
					12.7%	6.0550	333 ± 5	
20EQ88	Lava flow, Tanipamba (Pita valley)	786939	9949596	1.746	3.0%	5.3977	296 ± 11	295 ± 10
					3.9%	5.3573	294 ± 9	

1277 **Table 2.** Construction and erosion volumes calculated from numerical reconstructions. Results
 1278 are given with a 1- σ uncertainty (see text for details).

Volcano	Construction Volume (km ³)	Uncertainty percentage	Present-day Volume (km ³)	Erosion Volume (km ³)	Erosion percentage	Reference
Almas Santas	90 ± 14	15%	25 ± 10	67 ± 3	74%	This study
Atacazo	61 ± 7	12%	25 ± 6	36 ± 1	60%	This study
Carcacha	8 ± 1	12%	5 ± 1	3 ± 0	41%	This study
Corazón	31 ± 7	21%	9 ± 7	22 ± 0	71%	This study
Pasochoa	63 ± 6	10%	44 ± 5	19 ± 1	30%	This study
Rumiñahui	43 ± 10	24%	22 ± 10	21 ± 1	49%	This study
Santa Cruz	21 ± 3	15%	~16	~5	24%	This study
Sincholagua	42 ± 7	16%	11 ± 5	31 ± 2	74%	This study
Cotopaxi II	32 ± 3	9%	29 ± 3			This study
Quilindaña	25 ± 3	18%	9 ± 1	16 ± 1	63%	This study
North Iliniza	28 ± 9	32%	~22	6 ± 2	21%	Santamaría et al. (2022)
South Iliniza	18 ± 6	33%	~12	6 ± 2	33%	Santamaría et al. (2022)
Iliniza (whole)	46 ± 15	32%	34 ± 14	12 ± 4	26%	Santamaría et al. (2022)
Cotopaxi I – Barrancas stage	~32					Hall and Mothes (2008)
Cotopaxi I – Morurco stage	~4					Hall and Mothes (2008)
Cotopaxi II	~51					Hall and Mothes (2008)
Antisana (whole)	~50					Hall et al. (2017b)
Chalupas (bulk)	230 ± 30	8%				Bablon et al. (2020b)
Chalupas (DRE)	~100					Hall and Mothes (2008) Croweller et al. (2012)

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1281 **Table 3.** Generalized chronostratigraphy of the central volcanic cluster of the Ecuadorian arc
 1282 showing the main cone-building stages of its volcanoes

Volcano	NW-SE Alignment	Location	Cone-building stage	Magma Composition	Age (ka)	References
<i>Ancient volcanism</i>	All	North of lat. 0°20'S	E.g., Pichincha (El Cinto), Chacana (old lavas), Cayambe (Viejo Cayambe)		>1 Ma	Samaniego et al., (2005); Opdyke et al., (2006); Robin et al., (2010); Bablon et al., (2020a)
Almas Santas	Volcanic Front	lat. 0°35'S long. 78°51'W	Early stage (andesite lavas)	53-57 wt.% SiO ₂ medium-K series	~375 to ~365	Chemin, (2004); This study
			Late stage and Cerro Azul satellite lavas	57-63 and 67-75 wt.% SiO ₂ medium-K series	< 365 ka	Chemin, (2004); This study
Atacazo-Ninahuilca	Volcanic Front	lat. 0°19'S long. 78°36'W lat. 0°21'S long. 78°37'W	La Carcacha edifice	60-61 wt.% SiO ₂ medium-K series	~1.3 Ma	Hidalgo, (2006)
			Atacazo edifice and satellite lava domes	57-63 and 66-67 wt.% SiO ₂ medium-K series	~200 to ~71 ka	Hidalgo, (2006); This study
			Ninahuilca dome complex	61-66 wt.% SiO ₂ medium-K series	<8 ka	Hidalgo, (2006)
Corazón	Volcanic Front	lat. 0°32'S long. 78°40'W	Main Edifice	53-64 wt.% SiO ₂ medium-K series	~115 to ~70 ka	Chiaradia et al., (2009); This study
Iliniza	Volcanic Front	lat. 0°37'S long. 78°41'W lat. 0°39'S long. 78°43'W	Pilonga lava dome	68-69 wt.% SiO ₂ medium-K series	353 ± 6 ka	Hidalgo et al., (2007); Santamaría et al., (2022)
			North Iliniza edifice	62-65 wt.% SiO ₂ medium-K series	~125 to ~115 ka	Hidalgo et al., (2007); Santamaría et al., (2022)
			South Iliniza edifice and late satellite lavas	59-72 and 59-63 wt.% SiO ₂ medium-K series	~45 to ~6 ka	Hidalgo et al., (2007); Santamaría et al., (2022)
Paschocha	Inter-Andean Valley	lat. 0°28'S long. 78°29'W	Main Edifice	55-61 wt.% SiO ₂ medium-K series	~470 to ~425 ka	Schiano et al., (2010); This study
Rumiñahui	Inter-Andean Valley	lat. 0°35'S long. 78°30'W	Early stage	53-58 wt.% SiO ₂ medium-K series	>300 ka	Starr, (1984); This study
			Late stage	61-63 wt.% SiO ₂ high-K series	~210 ka	Starr, (1984); This study
Santa Cruz	Inter-Andean Valley	lat. 0°39'S long. 78°38'W	Main Edifice	56-66 wt.% SiO ₂ medium-K series	~700 ka	Santamaría et al., (2022)
			Loma Saquigua cone	58-64 wt.% SiO ₂ medium-K series	~80 to ~60 ka	Santamaría et al., (2022)
Sincholagua	Main arc	lat. 0°32'S long. 78°22'W	Main Edifice	59-61 wt.% SiO ₂ medium-K series	~310 ka	This study
Cotopaxi	Main arc	lat. 0°43'S long. 78°27'W	Barrancas stage	74-77 wt.% SiO ₂ medium- to high-K series	~540 ka	Hall and Mothes, (2008); Garrison et al., (2011); This study
			Morurco stage	57-63 wt.% SiO ₂ medium-K series	~335 to ~295 ka	Hall and Mothes, (2008); Garrison et al., (2011); This study
		lat. 0°41'S long. 78°26'W	Cotopaxi II	56-66 and 70-76 wt.% SiO ₂ medium- to high-K series	<13 ka	Hall and Mothes, (2008); Garrison et al., (2011)
Antisana	Main arc	lat. 0°29'S long. 78°08'W	Main Edifice	54-68 wt.% SiO ₂ medium- to high-K series	~400 to <0.8 ka	Hall et al., (2017b)
			Cuyuja lava flow	55-58 wt.% SiO ₂ high-K andesite series	210 ± 30 ka	Hall et al., (2017b)
Huañuna	Main arc	lat. 0°37'S long. 78°14'W	Lava dome	Rhyolitic lavas high-K series	~12 and ~10 ka	Mothes and Hall, (2008); Hall et al., (2017b)
Chaupiloma (Rio Valle)	Main arc	lat. 0°40'S long. 78°16'W	Lava dome	Rhyolitic lavas high-K series	~15 to 6 ka	Mothes and Hall, (2008); Hall et al., (2017b)
Chalupas-Quilindaña	Main arc	lat. 0°48'S long. 78°23'W	Pre-caldera lavas	55-71 wt.% SiO ₂ high-K series	~460 to ~420 ka	Hammersley, (2003); Córdova et al., (2020)

lat. 0°47'S long. 78°20'W	Caldera-forming ignimbrite eruption	73-76 wt.% SiO ₂ high-K series	216 ± 5 ka	Hammersley, (2003); Bablón et al., (2020b); Córdova et al., (2020)
lat. 0°47'S long. 78°20'W	Quilindaña	57-70 wt.% SiO ₂ high-K series	~185 to ~45 ka	Hammersley, (2003); Córdova et al., (2020)

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