

## Petrological and geochemical constraints on the magmatic evolution at the Ampato-Sabancaya compound volcano (Peru)

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### Abstract :

In order to gain insights into continental arc magmatic processes, we have conducted a petrological and geochemical study of major and trace elements and Sr, Nd, and Pb isotopes of the Ampato-Sabancaya compound volcano, which belongs to the Andean Central Volcanic Zone (CVZ). Whole-rock compositions for Ampato and Sabancaya range from andesites to dacites (56.7-69.3 wt% SiO<sub>2</sub>) and both belong to a medium- to high-K calcalkaline magmatic series. Ampato-Sabancaya samples are characterized by high contents of large-ion lithophile elements (LILE; e.g., K, Rb, Ba, Th), low concentrations of high field strength elements (HFSE; e.g., Nb, Zr) and heavy rare earth elements (HREE; e.g., Yb), with consequently high La/Yb and Sr/Y ratios. An increase in these ratios is usually interpreted as a result of magmatic differentiation in the presence of garnet in the deep crust. A detailed analysis reveals that the rocks of Ampato-Sabancaya display three different compositional groups. (1) The first, composed mainly of andesites (56.7-59.8 wt% SiO<sub>2</sub>), corresponds to lavas from the early stage of the Ampato Basal edifice, as well as pyroclastic deposits from the Ampato Upper edifice. (2) The second group corresponds to andesitic and dacitic compositions (60.0-67.3 wt% SiO<sub>2</sub>) from the Ampato Basal edifice (Moldepampa stage), the Ampato Upper edifice, and the Sabancaya edifice. (3) The third group corresponds to dacitic compositions (65.0-69.3 wt% SiO<sub>2</sub>) associated with the Corinta Plinian fallout and pyroclastic flow deposits from the Ampato Upper edifice. This last group of dacites, erupted during the Ampato Upper edifice stage, have drastically different compositions from the other groups with Sr/Y (<27) and Sm/Yb (<4.7) ratios lower than other lavas and lacking evidence of amphibole and/or garnet fractionation during their genesis. As a whole, Sr, Nd, Pd isotopic ratios suggest that mantle-derived magmas are significantly affected by assimilation processes during their evolution, due to the thick (65-70 km) continental crust beneath the CVZ in southern Peru. In summary, the magmatic evolution of group 1 and 2 can be explained

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by a two-step model in which primitive magmas evolved in the deep crust in the so-called melting-assimilation-storage-homogenization (MASH)-type reservoirs by assimilation-fractional crystallization (AFC) processes involving garnet and/or amphibole. Then, amphibole-dominated upper crustal AFC processes and magma mixing are responsible for the geochemical diversity of the main ASCV trend. In contrast, the group 3 dacites followed an upper crustal AFC process (without amphibole) from a different primitive magma, which did not suffer the high pressure, garnet-dominated AFC processes. This evolution highlights the complexities associated to magma genesis and differentiation at continental arcs constructed on a thick crust.

### Highlights

► Ampato-Sabancaya medium-high-K calc-alkaline suite range from andesites to dacites. ► Trace elements and isotope ratios indicate crustal assimilation processes. ► Geochemical modelling shows that AFC and magma mixing have controlled the evolution. ► Magma evolved by lower and upper crustal differentiation. ► The assimilated crust is the Arequipa Proterozoic basement.

**Keywords** : Ampato, Sabancaya, Central Andes, Arc magmatism, Magmatic evolution, Geochemistry, Assimilation -fractional crystallization, Magma mixing

## 62 **1. Introduction**

63           The volcanic arc along the Andean Cordillera results from the subduction of the  
64   oceanic Nazca plate below the continental South American plate. This volcanic arc is  
65   divided into three active arc segments, the Northern (NVZ), Central (CVZ), and Southern  
66   (SVZ) volcanic zones (Fig. 1a). In addition, the Austral volcanic zone (AVZ) results from  
67   subduction of the Antarctica plate below the South American plate. The CVZ is composed  
68   of volcanoes in southern Peru, Bolivia, and northern Chile and Argentina. This arc  
69   segment is constructed on one of world's thickest continental crusts and is considered the  
70   archetype for studying crustally-modified arc magmas (Barreiro and Clark, 1984;  
71   Harmon et al., 1984; Thorpe et al., 1984; Davidson et al., 1991; Mamani et al., 2010).

72           Quaternary lavas in the CVZ are high-K andesites, dacites and rhyolites that  
73   systematically display low heavy rare earth elements (HREE) and Y contents. In addition,  
74   these magmas are characterised by high  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\delta^{18}\text{O}$  ratios (typically  $>0.70534$  and  
75   8–12‰, respectively), low  $\epsilon\text{Nd}$  (-2–12), and relatively low  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios (17.3–19.0)

76 (Barreiro and Clark, 1984; James, 1982; Wörner et al., 1988; Davidson et al., 1991;  
77 Haschke et al., 2006; Delacour et al., 2007; Kay et al., 2010; Mamani et al., 2010; Rivera  
78 et al., 2017). Petrogenetic models for the CVZ consider that the primitive calc-alkaline  
79 magmas are derived from partial melting of a mantle wedge previously metasomatised by  
80 hydrous fluids released through dehydration of the subducted lithosphere. These mantle-  
81 derived magmas evolved by fractional crystallization coupled with crustal assimilation or  
82 partial melting during magma storage and ascent through the thick continental crust.

83         Given that the CVZ magmas have systematically high La/Yb, Sm/Yb and Sr/Y  
84 ratios, some researchers support the idea that evolution of these magmas is dominated by  
85 crustal partial melting with garnet present in the residue (Kay, 2002; Mamani et al., 2010).  
86 While other authors (e.g., Hildreth and Moorbath, 1988; Davidson et al., 1991; Freymuth  
87 et al., 2015) consider that both mantle-derived and crust-derived magmas may have mixed  
88 and/or mingled at deep levels in the high-pressure melting, assimilation, storage and  
89 homogenization (MASH) zones, thereby producing large volumes of contaminated  
90 andesitic magmas. This model has been corroborated through recent seismic imaging  
91 studies that show low seismic velocity zones throughout the crust which are interpreted  
92 as the upper part of trans-crustal MASH zones (Delph et al., 2017). As a complement of  
93 the MASH model, several studies highlight the role of low pressure AFC processes as an  
94 explanation of the compositional diversity of magmas erupted at the large compound  
95 CVZ volcanoes (e.g., James, 1982; Barreiro and Clark, 1984; Harmon et al., 1984; Thorpe  
96 et al., 1984; Vatin-Pérignon et al., 1992; Feeley and Sharp, 1995; Godoy et al., 2014;  
97 Rivera et al., 2017). Recently, Blum-Oeste and Wörner (2016) proposed a slightly  
98 different model in which magma mixing (instead of the AFC process) is the dominant  
99 process, and identified three geochemical end-members for the CVZ magmas: (1) a  
100 slightly evolved calc-alkaline, mantle-derived basaltic andesite; (2) an enriched, mantle-

101 derived, shoshonitic basalt; and, (3) a crust-derived rhyodacite. Following these authors,  
102 the variable proportions of these three end-members could explain the compositional  
103 variability of CVZ magmas.

104 In order to provide constraints on the crustal contribution of the CVZ magmas, we  
105 focus on the petrogenetic evolution of a single volcanic centre of this arc segment, the  
106 Ampato-Sabancaya compound volcano (ASCV), a large, late Pleistocene volcanic centre  
107 of the Peruvian CVZ. Previous studies on this volcanic centre focused on reconstructing  
108 the eruptive chronology and identifying a large magmatic diversity of silica-rich end-  
109 members (dacites and rhyolites) that could represent different modalities of the crustal  
110 processes ([Samaniego et al., 2016](#); [Rivera et al., 2016](#)). Based on a detailed reconstruction  
111 of the Ampato-Sabancaya eruptive chronology, we present major and trace element  
112 compositions, and Sr, Nd, and Pb isotope data for samples covering the entire Ampato-  
113 Sabancaya lifetime. These data record the compositional variations through the evolution  
114 of the Ampato-Sabancaya compound volcano and enable us to identify the main  
115 petrogenetical processes that control the composition of the erupted magmas. These  
116 hypotheses have been tested using different geochemical modelling approaches in order  
117 to describe the evolution of magma genesis at ASCV during the last 0.5 My.

118

## 119 **2. Regional geological setting**

120 In southern Peru, the CVZ arc segment results from subduction of the 40–45 Ma  
121 oceanic Nazca plate beneath the South American continental plate at a convergence  
122 direction of N80° and rate of 5–7 mm/yr ([Norabuena et al., 1998](#)). The resulting volcanic  
123 arc developed along the Western Cordillera and is constructed on continental crust  
124 reaching ~65-70 km thick along the main Andean keel ([Beck et al., 1996](#)). Geological  
125 mapping of the Western Cordillera indicates that the oldest rocks correspond to granulite-

126 facies gneisses (such as the Charcani gneiss portion of the Arequipa Massif, [Boily et al.,](#)  
127 [1989](#)) that crop out 32 km northwest (in Colca Canyon) and 34 km southwest of Ampato-  
128 Sabancaya volcano. The Arequipa Massif includes rocks with protolith ages of 1.9 Ga  
129 ([Dalmayrac et al., 1977](#)) and others with Mesoproterozoic protoliths and metamorphism  
130 ages of 1.2–1.0 Ga ([Wasteneys et al., 1995](#); [Loewy et al., 2004](#)). These rocks arguably  
131 occur at depth beneath the volcanic arc of southern Peru ([Harmon et al., 1981](#)). This older  
132 massif is unconformably overlain by weakly folded, Mesozoic marine clastic (Yura  
133 Group) and volcano-sedimentary formations that have been intruded by Paleogene  
134 granites and granodiorites belonging to the Coastal Batholith (Tiabaya super-unit; [Caldas,](#)  
135 [1973](#); [Romero and Ticona, 2003](#)). These formations are covered by Oligocene-Miocene  
136 volcanoclastic and volcanic sequences (Tacaza Group) that in turn are overlain by  
137 Pliocene-Pleistocene volcanic sequences (Barroso Group). Late Quaternary volcanoes,  
138 such as Ampato-Sabancaya, are constructed on top of a high-altitude plateau formed by  
139 the older Barroso and Tacaza volcanic sequences.

140         The Quaternary volcanic arc in southern Peru is composed of at least 14 andesitic  
141 and dacitic compound volcanoes and several monogenetic volcanic fields ([de Silva and](#)  
142 [Francis, 1991](#); [Siebert et al., 2010](#); [Bromley et al., 2019](#)) ([Fig. 1a, b](#)). During historical  
143 time (*i.e.*, following the Spanish conquest beginning in 1532 CE), six of these volcanoes  
144 have experienced eruptive activity: Sabancaya, El Misti, Ubinas, Huaynaputina, Ticsani,  
145 and Tutupaca ([Thouret et al., 2005](#); [Thouret et al., 2001](#); [Siebert et al., 2010](#); [Samaniego](#)  
146 [et al., 2015](#)). Some of these volcanoes experienced large explosive eruptions during the  
147 last few millenia and historical times, including the Plinian eruptions of El Misti (*c.* 2030  
148 yr BP, [Thouret et al., 2001](#); [Harpel et al., 2011](#)), Ubinas (*c.* 1000 yr BP, [Thouret et al.,](#)  
149 [2005](#); [Samaniego et al., 2020](#)), and Huaynaputina (1600 CE, [Prival et al., 2020](#)), as well  
150 as the collapse-triggered explosive eruption of Tutupaca (1787–1802 CE, [Samaniego et](#)

151 [al., 2015](#)). In addition, Ubinas and Sabancaya are among the most active Central Andean  
152 volcanoes, with several small-to-moderate magnitude eruptions during the last centuries.  
153 The most recent such eruptions occurred during 2006–2009 CE, 2013–2017 CE and 2019  
154 CE at Ubinas; and 1986–1998 CE and since 2016 CE at Sabancaya.

155

### 156 **3. Ampato-Sabancaya volcanological evolution**

157 The Ampato-Sabancaya compound volcano (ASCV, 15° 49.3'S, 71° 52.7'W) is  
158 located 75 km northwest of the city of Arequipa ([Fig. 1](#)), in the Western Cordillera of the  
159 Andean Central Volcanic Zone (CVZ, [Fig. 1a](#)). This compound volcano is situated  
160 southeast of the older, Pleistocene, Hualca Hualca edifice (6,025 m above sea level –  
161 a.s.l.). Ampato (6,280 m asl) and Sabancaya (5,980 m asl) form a massif, aligned along a  
162 N50° trend, decreasing in age from SW to NE. An andesitic lava flow emplaced over  
163 Pliocene ignimbrites forms the basement of the ASCV and has an age of  $0.80 \pm 0.04$  Ma  
164 ([Gerbe and Thouret, 2004](#)), constraining the initiation of growth for Ampato and  
165 Sabancaya volcanoes to have been during the middle or upper Pleistocene.

166

167 *Ampato* volcano covers an area of 90–100 km<sup>2</sup> with an approximate volume of 38–42  
168 km<sup>3</sup> ([Samaniego et al., 2016](#)). The volcano's current morphology is formed by at least  
169 three successive cones orientated SW-NE, hereafter termed the Southern, Central, and  
170 Northern cones, respectively located 1.2 and 2.5 km from the summit (the Southern cone)  
171 ([Fig. 2](#)). Ampato was affected by glacial erosion during the Last Glacial Maximum  
172 (LGM) which roughly occurred in this part of the Andes between 17 and 25 ka ([Bromley  
173 et al., 2009](#)). On Hualca Hualca volcano, cosmogenic exposure ages on blocks from LGM  
174 moraines indicate that this event occurred between 16 and 17 ka ([Alcalá-Reygosa et al.,  
175 2017](#)). This glacial event generated a variety of morphological features such as cirques

176 and U-shaped valleys on the western and southeastern flanks of Ampato. Following  
177 [Rivera et al. \(2016\)](#) and [Samaniego et al. \(2016\)](#), the eruptive chronology of Ampato  
178 compound volcano comprises:

179 (1) The Ampato Basal edifice ([Fig. 2](#)), which is an old, highly eroded volcano composed  
180 of a 600-m-thick succession of lava flows interlayered with scarce scoria-flow deposits  
181 (57.2–62.2 wt.% SiO<sub>2</sub>) and spatter agglutinates that crop out on the proximal  
182 southwestern and western flanks of Ampato (AMI-1, [Fig. 2](#)). We include in this older  
183 stage, a 200–400 m-thick medial-to-distal succession of sub-horizontal andesitic lava  
184 flows (57.2–61.9 wt.% SiO<sub>2</sub>) that crop out on the Jatun Pampa plain, on the southeast side  
185 of Ampato (AMI-2, [Fig. 2](#)). This, the oldest stage of the Ampato Basal edifice, was  
186 constructed between 450 ka and 400 ka ([Samaniego et al., 2016](#)). Another remnant of this  
187 edifice (Moldepampa stage, AMI-3, [Fig. 2](#)) consists of a 200–300 m-thick succession of  
188 dacitic lava flows (62.9–65.1 wt.% SiO<sub>2</sub>). Age determinations by [Samaniego et al. \(2016\)](#)  
189 on lavas of this stage yield dates of about 230–200 ka. [Samaniego et al. \(2016\)](#) and [Rivera](#)  
190 [et al. \(2016\)](#) assumed that a 4–5 m-thick succession of rhyolitic tephra-fall deposits (74.2–  
191 76.9 wt.% SiO<sub>2</sub>), which only crop out in the Chacramayo valley 10 km southwest of  
192 Ampato, were emplaced at the end of this stage. In this work, we challenge the origin of  
193 these rhyolitic deposits.

194 (2) The Ampato Upper edifice started with the Yanajaja stage (AMII-1, [Fig. 2](#)), which  
195 consists of a succession of andesitic and dacitic lava flows (61.8–63.5 wt.% SiO<sub>2</sub>) reaching  
196 200–300 m thick that outcrop on the south and southwest flanks of Ampato. A sample  
197 from this unit was dated at  $77 \pm 4$  ka. The successive construction of the Northern (AMII-  
198 2), Southern (AMII-3, 4, 6, 7), and Central (AMII-8) peaks is represented by lava flows  
199 and pyroclastic sequences with andesitic compositions (61.0–62.0 wt.% SiO<sub>2</sub>). Two lavas  
200 of the south and southeast flanks of the Upper edifice yielded ages of  $40 \pm 3$  and  $34 \pm 8$



201 ka, respectively. Associated with this volcanic stage are the thick (>20 m) block-and-ash  
202 flow deposits that crop out 5–6 km east and west of the Ampato summit (AMII-5, [Fig.](#)  
203 [2](#)). In addition, we include in this stage the scoria-rich Baylillas (56.7–59.0 wt.% SiO<sub>2</sub>)  
204 and Corinta (65.0–68.0 wt.% SiO<sub>2</sub>) tephra-fall and pyroclastic-density current deposits  
205 which crop out 10–12 km southwest of the volcano's summit. These pyroclastic  
206 successions are highly eroded and were likely emplaced before the LGM (i.e., 17–25 ka;  
207 [Bromley et al., 2009](#); [Alcalá-Reygoza et al., 2017](#)). The central cone was discordantly  
208 constructed over the remnants of the northern and southern cones of the Ampato Upper  
209 edifice ([Fig. 2](#)). It is composed of a sequence of andesitic and dacitic (61.3–66.0 wt.%  
210 SiO<sub>2</sub>) lava flows, with a maximum thickness of 400–600 m. A lava sample from this unit  
211 was dated at  $17 \pm 6$  ka ([Samaniego et al., 2016](#)). An oblate, andesitic (61.3 wt.% SiO<sub>2</sub>)  
212 lava dome lacking evidence for glacial erosion is located at the top of the northern cone  
213 between 5,700 m asl and 6,000 m asl and is Ampato volcano's youngest feature.

214

215 *Sabancaya* volcano covers an area of 65–70 km<sup>2</sup> and comprises a volume of approximately  
216 6–10 km<sup>3</sup> ([Samaniego et al., 2016](#)). Sabancaya is located northeast of the older Ampato  
217 edifice and has two coalescing cones orientated in a SW-NE direction. Sabancaya's  
218 eruptive chronology started with the older Basal edifice, which is represented by a  
219 sequence of blocky, andesitic-dacitic (60.6–65.6 wt.% SiO<sub>2</sub>) lava flows (SA-1) that  
220 spilled out onto the older rocks of the Ampato and Hualca Hualca edifices. These blocky  
221 lava flows have individual thicknesses of 40–80 m, forming a 300–400 m thick lava pile  
222 that extends as far as 8 km from the west to southeast of the summit ([Fig. 2](#)). A lava flow  
223 from this stage was dated at  $6.30 \pm 0.31$  ka by <sup>3</sup>He surface-exposure dating ([Samaniego](#)  
224 [et al., 2016](#)). We include in this stage the 400 m-high lava dome that forms the  
225 southwestern part of Sabancaya's current summit (SA-2); as well as three andesitic (60.9–

226 62.5 wt.% SiO<sub>2</sub>) lava flow successions (SA-3) emplaced on the Sallalli plain (Fig. 2).  
227 [Bulmer et al. \(1999\)](#) and [Samaniego et al. \(2016\)](#) linked this sequence to a satellite vent  
228 located 4 km to the southwest of the active crater. Two samples from these blocky lava  
229 flows were dated by [Samaniego et al. \(2016\)](#) at  $6.65 \pm 0.32$  ka and  $12.34 \pm 0.55$  ka by <sup>3</sup>He  
230 surface-exposure dating (Fig. 2). More recently, [Bromley et al. \(2019\)](#) measured helium  
231 concentrations in two additional samples from Sabancaya lavas, obtaining ages of  $5.2 \pm$   
232  $0.1$  ka and  $4.1 \pm 0.1$  ka (Fig. 2). In addition, a lava flow emplaced on the western flank of  
233 the volcano covering a peat bog yielded an age of  $5,440 \pm 40$  <sup>14</sup>C yr BP ([Gerbe and](#)  
234 [Thouret, 2004](#)). Based on such geochronological information, Sabancaya's Basal edifice  
235 was constructed during the Holocene.

236 Sabancaya's eruptive chronology continued during the Late Holocene with the  
237 construction of a younger cone represented by a sequence of lava flows (SA-4) emplaced  
238 discordantly upon the lavas of the previous stage. These lava flows reach 4–5 km from  
239 the vent, have a thickness of 40–60 m and consist of andesites and dacites (61.7–65.7  
240 wt.% SiO<sub>2</sub>). This cone is covered by pyroclastic material and includes an active, semi-  
241 circular summit crater (Fig. 2) and a maximum diameter of 290 m. Explosive activity of  
242 Sabancaya continued until historic times. Two well-preserved ash-rich tephra-fall  
243 deposits in the Sallalli peat bog southeast of Sabancaya were emplaced between 4.5 ka  
244 and 3 ka ([Samaniego et al., 2016](#)). In the Quebrada Huaraya section, a 10–30 cm-thick  
245 coarse ash layer was found, where the underlying peat yielded an age of  $265 \pm 30$  <sup>14</sup>C yr  
246 BP. This age agrees with the  $300 \pm 50$  <sup>14</sup>C yr BP date obtained by [Juvigné et al. \(2008\)](#)  
247 and confirms the occurrence of explosive eruptions during the 17<sup>th</sup> or 18<sup>th</sup> century  
248 ([Travada and Córdova, 1752](#)).

249 During the 20<sup>th</sup> century, eruptive activity resumed at Sabancaya, lasting from  
250 1986 until 1998. In December 1986, Sabancaya experienced enhanced fumarolic activity

251 followed by an increase of explosive activity that culminated with an eruption (VEI 2) on  
252 29 May 1990 (Gerbe and Thouret, 2004). Explosions generated columns of ash and gas  
253 that rose 1–5 km above the crater during which ash was dispersed as far as 12 km from  
254 the summit. Then, recurrent at low to moderate explosive activity continued until 1998.  
255 The bulk volume of the tephra emitted during the major phase of the eruption from May  
256 to October 1990 was roughly estimated as 0.025 km<sup>3</sup> (Thouret et al., 1994). In 2013,  
257 Sabancaya experienced a significant increase in seismic activity and gas emissions that  
258 eventually rose to 2,000 m above the summit. Subsequently, in November 2016, a new  
259 eruptive period began and is ongoing through the time of writing (May 2023). This  
260 eruptive activity is characterised by vulcanian explosions associated with frequent gas  
261 and ash emissions which in July 2017 formed eruption columns reaching up to 5,000 m  
262 above the summit. Associated with the 2016–2020 eruptive activity, we observe newly  
263 emplaced lava domes inside the summit crater.

264

## 265 **4. Sample collection and preparation, and analytical methods**

### 266 **4.1. Field sampling and sample preparation**

267 Geological mapping, stratigraphic studies and sampling were conducted during  
268 several field campaigns between 2009 and 2020. We collected 138 samples that are  
269 representative of most volcanic units (Fig. 2).

270

### 271 **4.2 Analytical methods**

#### 272 *4.2.1. Mineral analyses*

273 Thin sections of all samples were prepared for petrographic studies and electron  
274 microprobe analysis. The mineral analyses for 26 samples were obtained using a  
275 CAMECA SX-100 electron microprobe at the Laboratoire Magmas et Volcans

276 (Université Clermont Auvergne, Clermont-Ferrand, France). Operating conditions for  
277 mineral analyses were 15 keV accelerating voltage, 10 nA beam current and 10 s counting  
278 time. The estimated error for a single analysis is about 1% when the element concentration  
279 is higher than 10%, whereas for element concentrations lower than 10% uncertainty is 2–  
280 5%. Composition data for phenocrysts from each volcanic unit are presented in  
281 Supplementary Electronic Material ([SEM 1](#)).

282

#### 283 *4.2.2. Major and trace element whole-rock analyses*

284 Major and trace element concentrations in 132 whole-rock samples were  
285 determined at the Laboratoire Geosciences Océan, Université de Bretagne Occidentale  
286 (Brest, France). Agate-ground powders were dissolved in HNO<sub>3</sub> and HF and then  
287 measured by ICP-AES (Inductively Coupled Plasma-Atomic Emission Spectroscopy),  
288 following the procedure of [Cotten et al. \(1995\)](#). Relative standard deviations are 1% for  
289 SiO<sub>2</sub> and <2% for the other major element oxides, except for low concentrations  
290 (<0.50%), for which the absolute standard deviation is 0.01%. For trace elements, the  
291 relative standard deviation is *ca.* 5%. Calibrations were performed using international  
292 standards JB2, BEN, ACE, WS-E, PM-S as well as specific reference samples. All  
293 analyses were recalculated on an anhydrous basis with iron expressed as Fe<sub>2</sub>O<sub>3</sub>\*. We add  
294 to the database 6 major and trace element analyses from the 1990 eruptive products  
295 published by [Gerbe and Thouret \(2004\)](#). Representative whole-rock analyses are  
296 presented in [Table 1](#), while all whole-rock analyses are presented in [SEM 2](#).

297

#### 298 *4.2.3. Sr, Nd, and Pb whole-rock analyses*

299 Sr and Nd isotope analyses of 37 samples from Ampato and Sabancaya lavas were  
300 performed at the Laboratoire Magmas et Volcans (Clermont-Ferrand, France) on whole-

301 rock powders, which were dissolved using an HF/HNO<sub>3</sub>/HClO<sub>4</sub> mixture. Sr and Nd were  
302 separated by ion-exchange chromatography according to the procedures described in [Pin](#)  
303 [et al. \(1994\)](#) and [Pin and Santos-Zalduegui \(1997\)](#). <sup>87</sup>Sr/<sup>86</sup>Sr and <sup>143</sup>Nd/<sup>144</sup>Nd isotopic  
304 ratios were determined using either a VG Isomass 54E multicollector mass spectrometer  
305 or a Finnigan TRITON. During the period of measurements, SRM-987 and AMES  
306 Rennes standards gave <sup>87</sup>Sr/<sup>86</sup>Sr=0.710239 ± 0.00002 (2σ, n=4) and  
307 <sup>143</sup>Nd/<sup>144</sup>Nd=0.5119651 ± 0.000015 (2σ, n=4). Six additional Sr/Nd isotopic ratios  
308 published by [Gerbe and Thouret \(2004\)](#) and three published by [Mamani et al. \(2010\)](#) are  
309 also included. Pb isotopic ratios were measured by MC-ICP-MS (Multicollector  
310 Inductively Coupled Plasma Mass Spectrometer) at Laboratoire Magmas et Volcans  
311 (Clermont-Ferrand, France) following the procedure described by [Nauret et al. \(2018\)](#).  
312 Pb isotope ratios are normalized to values of the NIST SRM 981 standard provided in  
313 [Galer and Abouchami \(1998\)](#). Selected whole-rock major and trace elements, and Sr, Nd,  
314 and Pb isotopic ratios are presented in [Table 1](#) and all the data are in [SEM 2](#).

315

## 316 **5. Characterisation of Ampato-Sabancaya volcanic rocks**

### 317 **5.1. Petrography and mineral chemistry**

318 Textures and mineral assemblages are similar throughout the ASCV rocks. The  
319 lava and pyroclastic deposits of ASCV are often porphyritic with intersertal and/or  
320 vitreous groundmass ([Fig. 3](#)). Ampato eruptive products are dominated by andesitic  
321 (~50%) and dacitic compositions (~46%), although some scarce (~4%) rhyolitic samples  
322 were also reported ([Table 2](#)). The lavas contain up to 30 vol.% phenocrysts, which are  
323 generally 0.2–3.0 mm and rarely up to 6.0 mm, and are variably vesicular (2–8 vol.%).  
324 Less than 8% of the lavas are subaphyric to poorly porphyritic, especially the lavas of the  
325 Ampato Basal edifice. The pyroclastic products contain between 10–30 vol.%

326 phenocrysts, which are generally 0.2–2.2 mm and rarely up to 4.0 mm, and are variably  
327 vesicular (10–60 vol.%). Ampato andesites have a phenocryst assemblage of plagioclase  
328 (Pl), clinopyroxene (Cpx), amphibole (Amp), biotite (Bt), and magnetite (Mag) together  
329 with scarce orthopyroxene (Opx), and olivine (Ol). The Ampato dacites host phenocrysts  
330 of Pl + Cpx + Bt + Amp + Mag and scarce Opx. The fine-grained groundmass of these  
331 rocks consists of Pl + Cpx + Amp + Mag, and scarce colourless to brownish interstitial  
332 glass. The rhyolites contain Pl + Bt + Mag and scarce alkali feldspar (Kfs) and quartz  
333 (Qz).

334         Some dense juvenile blocks belonging to block-and-ash flow deposits from the  
335 Ampato Upper edifice have dark brown and light gray bands. The dark brown bands  
336 contain phenocrysts of plagioclase (20–25 vol.%), amphibole (5–10 vol.%),  
337 clinopyroxene (2–4 vol.%), and biotite (2–4 vol.%), included within a vesicular matrix.  
338 In contrast, the light gray bands contain less phenocrysts than the dark brown bands and  
339 have an assemblage of plagioclase (2–4 vol.%), biotite (2–4 vol.%), and clinopyroxene  
340 (1–2 vol.%) within a glassy matrix.

341         Sabancaya's eruptive products are andesitic (~62%) and dacitic (~38%) in  
342 composition ([Table 2](#)). The lavas contain up to 30 vol.% phenocrysts, which are generally  
343 0.2–4.0 mm and rarely up to 7.0 mm. Samples are variably vesicular, with <8 vol.% for  
344 lavas and 4–10 vol.% for pyroclastic products. All andesites and dacites (e.g., SA-1, SA-  
345 2, SA-3) have an assemblage of Pl, Amp, Bt, Cpx, and Mag together with scarce Opx,  
346 and Ol. While such mineral phases are ubiquitous, their relative proportions are variable.  
347 The fine-grained groundmass (<80 µm) consists of Pl, Amp, Cpx, Mag, and scarce  
348 colourless, grey, or brownish interstitial glass.

349         The eruptive products emitted during the 1990–1998 eruption are andesites and  
350 dacites (60–64 wt.% SiO<sub>2</sub>). According to [Gerbe and Thouret \(2004\)](#), all eruptive products

351 are porphyritic with 20-25 vol.% phenocrysts. Some dense juvenile blocks have dark  
352 brown and light grey bands. The mineral assemblage consists of plagioclase (0.2–4 mm),  
353 amphibole (>0.2 mm), clinopyroxene, biotite, and Fe-Ti oxides. Eruptive products  
354 emitted during the 2017 CE eruptions are homogeneous, porphyritic andesites (60-61  
355 wt.% SiO<sub>2</sub>), with 40-50 vol.% phenocrysts. These andesites have a mineral assemblage  
356 consisting of plagioclase (20–25 vol.%), amphibole (4–6 vol.%), clinopyroxene (4–6  
357 vol.%), orthopyroxene (<1-2 vol. %), biotite (<1-2 vol. %) and Fe-Ti oxides.

358

### 359 *5.1.1. Plagioclase*

360 Plagioclase is the most abundant phenocryst phase in Ampato-Sabancaya rocks  
361 and occurs as euhedral to subhedral phenocrysts (20-40 vol.%) as well as microlites ([SEM](#)  
362 [1](#)). Based on textural and chemical characteristics, we identify two different plagioclase  
363 populations: (1) euhedral, non-altered phenocrysts with normal, oscillatory and/or reverse  
364 zoning patterns; and (2) sieve-cored or sieve-ringed phenocrysts with frequent dissolution  
365 zones and overgrowth rims displaying strong reverse zoning. In samples from Ampato  
366 Basal edifice, the anorthite content in plagioclase ranges from labradorite to oligoclase  
367 (An<sub>24-72</sub>, [Table 3](#), [SEM 3](#)). In Ampato Upper andesites the plagioclase is bytownite,  
368 labradorite, andesine, and oligoclase (An<sub>28-75</sub>), while in Ampato Upper dacites (including  
369 those of the Corinta unit) the plagioclase is labradorite, andesine, and oligoclase (An<sub>28-</sub>  
370 <sub>57</sub>). In both eruptive stages, normal zoning is frequent while reverse zoning is scarce. In  
371 Sabancaya andesites and dacites the anorthite content of plagioclase includes labradorite,  
372 andesine, and oligoclase (An<sub>27-63</sub>). Normal zoning is frequent in some phenocrysts while  
373 reverse zoning is scarce. In the products of the 1990 activity, the composition varies  
374 from oligoclase to labradorite (An<sub>26-62</sub>), of which andesine is predominant ([Gerbe](#)  
375 [and Thouret, 2004](#)). The andesites contain a mixed population of plagioclase

376 phenocrysts: Ca-rich clear plagioclase (An<sub>40-60</sub>), Na-rich clear plagioclase (An<sub>25-35</sub>),  
377 and inversely zoned “dusty rimmed” plagioclase with a sodic core (An<sub>25-40</sub>)  
378 surrounded by a Ca-rich overgrowth rim (An<sub>45-65</sub>) (Gerbe and Thouret, 2004). In the  
379 juvenile blocks of the 2017 CE eruptions the composition varies from andesine to  
380 labradorite (An<sub>36-55</sub>).

381

### 382 5.1.2. Clinopyroxene

383 Clinopyroxene occurs as euhedral to subhedral phenocrysts (<8 vol.%; up to 1  
384 mm in size) as well as microlites in the andesites and dacites (Table 2). In Ampato  
385 andesites and dacites (from both Basal and Upper edifices) clinopyroxenes have a  
386 restricted compositional range from diopside to magnesian augite (En<sub>39-46</sub>-Fs<sub>12-19</sub>-Wo<sub>40-</sub>  
387 <sub>47</sub>, following Morimoto et al. 1988) with Mg# [where Mg# = 100\*Mg/(Mg + Fe<sup>T</sup>) in  
388 mol.%, and Fe<sup>T</sup> is total iron as Fe<sup>2+</sup>] from 74–84 (Table 3, SEM 1, SEM 4). They generally  
389 are normally zoned (e.g., SA-1102: Mg# 80-76), but rare reverse zoning also exists (e.g.,  
390 SA-1137: Mg# 72-76). In Sabancaya andesites and dacites, clinopyroxenes also have a  
391 homogeneous compositional range from diopside to magnesian augite (En<sub>38-48</sub>-Fs<sub>11-17-</sub>  
392 <sub>Wo<sub>40-46</sub></sub>) with Mg# 72-85 (SEM 1 and SEM 4). They generally have normal (e.g., SA-  
393 0907: Mg#79-76) and reverse zoning patterns (e.g., SA-1152: Mg#73-79). The rocks of  
394 the 1990-1998 eruption contain clinopyroxenes, essentially augites (En<sub>40-46</sub>-Fs<sub>15-16</sub>-Wo<sub>40-</sub>  
395 <sub>46</sub>), similar to the rocks from the 2017 CE eruption (En<sub>41-43</sub>-Fs<sub>15-16</sub>-Wo<sub>40-43</sub>) with Mg#  
396 ranging from 77 to 79. Additionally, some Sabancaya and Ampato Upper edifice (AMII-  
397 3) clinopyroxene are Mg- and Cr-rich (Mg# 72-78, up to 0.1 wt % Cr<sub>2</sub>O<sub>3</sub>) (SEM 4). These  
398 high Mg# and Cr<sub>2</sub>O<sub>3</sub> contents suggest that these minerals crystallized from more primitive  
399 magmas.

400



### 401 5.1.3. Orthopyroxene

402 Euhedral and subhedral orthopyroxene are present as phenocrysts and microlites  
403 (<8 vol. %; up to 1 mm in size) in most andesites and some dacites (Table 3). In Ampato  
404 andesites and dacites, orthopyroxene has a compositional range from En<sub>62-76</sub> (Table 3,  
405 SEM 1 and SEM 4). While in andesites from Sabancaya they have a compositional range  
406 from En<sub>41-76</sub>. The orthopyroxene of the Ampato andesites are slightly less magnesian  
407 compared to Sabancaya orthopyroxene. In Ampato and Sabancaya rocks, orthopyroxene  
408 has slight normal zoning patterns (e.g., Ampato andesite SA-1033C: Mg# 75–72;  
409 Sabancaya andesite SA-0907: Mg# 78–76) and scarce reverse zoning (e.g., Ampato dacite  
410 SA-0930: Mg# 72–78; Sabancaya andesite SA-0906: Mg# 66–78). The orthopyroxene  
411 from the 2017 CE eruptions have homogeneous compositions (En<sub>71-72</sub>). Orthopyroxene is  
412 absent in the rhyolites.

413

### 414 5.1.4. Amphibole

415 Amphibole phenocrysts are present in different modal proportions (up to 10  
416 vol.%; up to 4 mm in size) in andesite and dacite lavas and pyroclastic products from  
417 Ampato and Sabancaya (Table 3). They are an accessory phase (~1 vol.%) in some  
418 Ampato Basal andesites, with subhedral forms and frequent, thin opaque (black) reaction  
419 rims. In contrast, amphibole phenocrysts in the Ampato Upper and Sabancaya andesites  
420 and dacites are much more abundant (2–10 vol.%), are euhedral and subhedral, and  
421 display scarce disequilibrium features. Indeed, thin opaque (black) reaction rims are  
422 sometimes observed, and very scarcely some amphiboles are completely replaced  
423 (pseudomorphs) by Fe-Ti oxides and pyroxene aggregates (e.g., SA-0918, 0911).  
424 Amphibole phenocrysts in Ampato Basal rocks have magnesio-hastingsite compositions  
425 while those of Ampato Upper and Sabancaya are edenite, magnesio-hastingsite,

426 magnesio-hornblende, and tschermakite (SEM 3) (Leake et al., 1997). Values of Mg# for  
427 amphibole in Ampato andesites and dacites vary from 70–83. There is minimal variation  
428 of Mg# among the different eruptive stages of Ampato, although normal (e.g., andesite  
429 SA-1155: Mg# 74-71) and reverse zoning are observed (e.g., dacite SA-1127C: Mg# 74-  
430 78). The amphiboles in Sabancaya andesites and dacites have Mg# values that vary from  
431 70–89, with mainly normal (e.g., andesite SA-0907: Mg# 85-79) and reverse zoning  
432 patterns (e.g., dacite SA-1015: Mg# 71-73). The rocks from the 2017 CE eruptions  
433 contain amphiboles with magnesium-hornblende and magnesium-hastingsite  
434 compositions (Mg# 72-77).

435

#### 436 5.1.5. Biotite

437 Biotite crystals occur in andesites, dacites, and rhyolites from Ampato and  
438 Sabancaya (SEM 1). Biotite (up to 6 vol.%, up to 3 mm in size) has euhedral and subhedral  
439 habits. Some phenocrysts have inclusions of plagioclase, clinopyroxene, and Fe-Ti oxide  
440 microlites. In some lavas, biotite crystals are armored by opaque minerals and plagioclase  
441 microlites (e.g., SA-0905; SA-0919). Ampato biotite is characterized by high proportions  
442 of  $\text{Fe}^{+2}/(\text{Fe}^{+2}+\text{Mg})$  (0.34-0.61) while Sabancaya biotite have narrow  $\text{Fe}^{+2}/(\text{Fe}^{+2}+\text{Mg})$   
443 values (0.40-0.44). All biotite crystals display high  $\text{Al}_2\text{O}_3$  (11.4-29.5 wt.%) (Table 2,  
444 SEM 1), and  $\text{TiO}_2$  (3.8-5.9 wt.%) concentrations, whereas Mg# is relatively low (49-66).

445

#### 446 5.1.6. Olivine

447 Olivine appears only as an accessory phase (<2 vol.%) in mafic andesites of  
448 Ampato Basal stage (Table 2 and 3) and are mostly subhedral and anhedral phenocrysts  
449 (<0.8 mm). The olivines have low magnesium content with forsterite (Fo) contents that  
450 vary in the range  $\text{Fo}_{68-77}$ . The phenocrysts have subtle normal zoning (e.g., SA-1102:

451 Fo<sub>73-72</sub>). In Sabancaya, olivine is scarce and appears in some andesitic lavas with slightly  
452 higher forsterite contents in the range Fo<sub>80-82</sub>. In this group, weak normal zoning is  
453 observed (e.g., SA-0906: Fo<sub>80-82</sub>).

454

#### 455 *5.1.7. Fe-Ti oxides*

456 Fe-Ti oxides (with sizes >40 µm) are present in the groundmass or as inclusions  
457 within pyroxenes, biotite, amphibole, and some olivine phenocrysts. All studied samples  
458 contain titano-magnetite, while some high-silica andesites and dacites of Sabancaya and  
459 Ampato also contain scarce ilmenite (SEM 1).

460

#### 461 *5.1.8. Accessory minerals*

462 Quartz appears as anhedral microphenocrysts in the most silica-rich samples (SiO<sub>2</sub>  
463 >70 wt.%) or as small grains in the groundmass of some dacites. Alkaline feldspars appear  
464 as phenocrysts of sanidine (Or<sub>70-71</sub>, Table 3, SEM 3) in some rhyolites. Apatite is found  
465 as inclusions in almost all mineral phases (amphibole, biotite, pyroxenes, and  
466 plagioclase).

467

## 468 **5.2. Main geochemical characteristics**

### 469 *5.2.1. Major and trace elements*

470 All analysed samples plot in the high-K calc-alkaline field of Peccerillo and  
471 Taylor (1976) (Fig. 4). The rocks of Ampato have a wide compositional range between  
472 basic andesites to dacites (56.7–69.33 wt.% SiO<sub>2</sub>; 2.0–4.9 wt.% K<sub>2</sub>O) while those of  
473 Sabancaya range between andesites and dacites (60.0–65.7 wt.% SiO<sub>2</sub>; 2.7–3.6 wt.%  
474 K<sub>2</sub>O). In this analysis, we also include the rhyolitic deposits that crop out to the west of  
475 Ampato-Sabancaya. The eruptive products of the 1990-1998 activity are andesites and

476 dacites (60.6–63.8 wt.% SiO<sub>2</sub>), while the eruptive products of the 2017 activity are mainly  
477 andesitic (58.2–61.2 wt.% SiO<sub>2</sub>).

478 In general, the ASCV samples display a single magmatic trend, but a more  
479 detailed analysis reveals that four different groups are present. (1) the first group,  
480 composed mainly of andesites (56.7–59.8 wt.% SiO<sub>2</sub>), corresponds to lavas from the  
481 early andesitic stage of the Ampato Basal edifice, as well as to the scoriaceous tephra-  
482 fall and pyroclastic-flow deposits of Ampato Upper edifice (Fig. 4). These samples  
483 are porphyritic lavas and tephra with plagioclase, ortho- and clinopyroxene, and Fe-  
484 Ti oxides. (2) The second group corresponds to andesitic and dacitic compositions  
485 (60.0–67.3 wt.% SiO<sub>2</sub>) from the Moldepampa stage, Ampato Upper edifice, and  
486 Sabancaya edifice. All these samples are porphyritic with phenocrysts of plagioclase,  
487 amphibole, biotite, ortho- and clinopyroxene, and Fe-Ti oxides. (3) The third group  
488 corresponds to dacitic compositions (65.0–69.3 wt.% SiO<sub>2</sub>) associated with the Corinta  
489 Plinian tephra-fall and pyroclastic-flow deposits of the Ampato Upper edifice (Fig. 4). (4)  
490 A final group consists of the rhyolites (74.2–76.9 wt.% SiO<sub>2</sub>) that correspond to tephra-  
491 fall deposits ascribed by Samaniego et al. (2016) to the Ampato Basal edifice.

492 A compositional evolution over time is not apparent. When plotted in Harker  
493 diagrams (Fig. 4), the andesites and dacites do not align along a single trend, and are  
494 separated from the rhyolitic eruptive products by a compositional gap between 69 wt.%  
495 SiO<sub>2</sub> and 74 wt.% SiO<sub>2</sub>. In binary diagrams (Fig. 4), all major oxides (except K<sub>2</sub>O) are  
496 negatively correlated to SiO<sub>2</sub>, whereas trace elements show positive correlations with  
497 silica, especially for the Large-Ion Lithophile Elements (LILE, e.g., Rb, Th, Ba). In these  
498 diagrams, compared to dacites of group 2, group 3 dacites have slightly elevated  
499 concentrations in some major and trace elements (e.g., K<sub>2</sub>O, Al<sub>2</sub>O<sub>3</sub>, Rb, Zr, Sm, La, Yb),  
500 and lower concentrations for other elements (e.g., MgO, CaO, Sr, Ni, Cr). The Rare Earth

501 Elements (REE) have a noteworthy pattern because the Middle REE (MREE, e.g., Sm)  
502 and Heavy REE (HREE, e.g., Dy, Yb) are reversely correlated with silica. In contrast,  
503 High Field Strength Elements (HFSE, e.g., Nb) are positively correlated, while Light REE  
504 (LREE, e.g., La, Ce) have a subtle positive correlation. Additionally, Y, Zr, Sr, and the  
505 transition metals (e.g., Sc, V, Cr, Ni) are negatively correlated with silica. Lastly, the  
506 rhyolites plot along the trend defined by group 2, except for LREE (e.g., La, Ce), LILE  
507 (e.g., Th), and HFSE (e.g., Nb).

508 Multi-element diagrams normalised to primitive mantle (Sun and McDonough,  
509 1989) suggest that Ampato-Sabancaya lavas are typical of continental arc magmas (Fig.  
510 5). Compared to the primitive mantle, these samples are enriched (~100 times) in LILE  
511 (e.g., Ba, Rb, Th, K) and LREE (e.g., La, Ce). The HFSE (e.g., Nb and Zr) show a marked  
512 negative anomaly as well as P and Ti. The rhyolites have more prominent P and Ti  
513 anomalies than group 3 dacites, which are in turn more prominent than group 2 dacites.

514 The REE patterns normalised to chondrites (Sun and McDonough, 1989) for  
515 ASCV rocks are almost parallel and have large LREE enrichments ( $77.5 < La_N < 247.5$ ) and  
516 HREE depletions ( $4.7 < Yb_N < 10.8$ ). In contrast, group 4 rhyolites have univesally lower  
517 REE contents with respect to groups 1 and 2 rocks, while group 3 dacites have higher  
518 values of MREE and HREE compared to groups 1, 2, and 4. The REE patterns for most  
519 andesites and dacites are also characterized by a relatively weak Eu anomaly (Fig. 5).  
520 Indeed, a detailed analysis of the behavior of HREE and other trace elements shows that  
521 the rhyolite samples do not follow the same geochemical trend, precluding a single  
522 differentiation process linking Ampato-Sabancaya andesites and dacites with the  
523 rhyolites (even if we include allanite and/or monazite as accessory minerals in the  
524 cumulate).

525

526 5.2.2. Isotopic ratios

527 The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the Ampato-Sabancaya andesite and dacite lavas range from  
528 0.70633–0.70765, while the  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios range from 0.51229–0.51243 (Table 1,  
529 Fig. 6). The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the rhyolites range from 0.7072–0.7088, while the  
530  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios range from 0.51211–0.51230 (Fig. 6). Excluding these rhyolitic  
531 compositions, the most radiogenic Sr values (and conversely the most unradiogenic Nd  
532 values) are displayed by group 3 dacites from the Ampato Upper edifice (Fig. 6b).

533 In the  $^{87}\text{Sr}/^{86}\text{Sr}$  versus  $^{143}\text{Nd}/^{144}\text{Nd}$  diagram (Fig. 6a), the Ampato-Sabancaya  
534 samples display a negative correlation and plot far from the mantle domain represented  
535 by the MORB field. Sr and Nd isotopic data have broadly homogeneous values at the  
536 scale of the CVZ (Davidson et al., 1991; Fig. 6a). Such characteristics suggest that ASCV  
537 magmas are contaminated by the continental crust, an interpretation corroborated by a  
538 positive correlation observed in the  $^{87}\text{Sr}/^{86}\text{Sr}$  versus  $\text{SiO}_2$  diagram (Fig. 6b). This  
539 relationship between  $\text{SiO}_2$  content (or any other differentiation index) and the isotopic  
540 composition of Ampato-Sabancaya magmas provides strong evidence for contamination  
541 by continental crust, possibly through an AFC process or magma mixing involving a  
542 crustally-derived end-member.

543 The  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios of the andesites and dacites eruptive products range from  
544 18.172 to 18.489, the  $^{207}\text{Pb}/^{204}\text{Pb}$  ratios range from 15.612 to 15.625, and the  $^{208}\text{Pb}/^{204}\text{Pb}$   
545 ratios are from 38.546 to 38.715 (Table 1). In contrast, the rhyolites display very  
546 heterogeneous lead isotopic values ( $^{206}\text{Pb}/^{204}\text{Pb}$ : 17.817–18.214;  $^{207}\text{Pb}/^{204}\text{Pb}$ : 15.599–  
547 15.614;  $^{208}\text{Pb}/^{204}\text{Pb}$ : 38.469–38.715). We stress that least differentiated sample (SA-  
548 1033E, Fig. 7) display the highest Pb isotopic ratios. The Ampato-Sabancaya samples plot  
549 in the typical fields for the Andean Central Volcanic Zone field (Mamani et al., 2010),  
550 southern part of Arequipa segment, and northern part of the Toquepala segment of the Peruvian

551 Coastal batholith (Mukasa, 1986) (Figs. 7a, b). In some diagrams (Fig. 7), the samples show  
552 a well-defined negative correlation pointing towards the Charcani gneiss field from the  
553 Arequipa Massif (Figs. 7c, d). Similar to the Sr isotope data, group 3 and group 2 dacites  
554 have homogeneous Pb isotope compositions, with lower  $^{206}\text{Pb}/^{204}\text{Pb}$  for a given  
555  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  value compared to andesites. A low  $^{206}\text{Pb}/^{204}\text{Pb}$  reflects the  
556 influence of Precambrian-age crust such as the Arequipa massif of southern Peru  
557 (Barreiro and Clark, 1984; James, 1982; Mamani et al., 2010).

558 The lead isotopic data (Figs. 7c, d) shows that most samples plot in a roughly  
559 linear distribution. However, dacites from group 3 and some samples of Ampato Upper  
560 edifice (group 2) have systematically low  $^{206}\text{Pb}/^{204}\text{Pb}$  and high  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$   
561 values. This distribution cannot be explained by a single assimilation-fractional  
562 crystallization or binary mixing process, suggesting that at least three end-members must  
563 be involved. We consider this hypothesis in the following sections and propose a model  
564 that accounts for magma mixing, fractional crystallization, and different crustal  
565 contaminants.

566

### 567 5.2.3. Temporal change in magma composition

568 Figure 8 plots selected major and trace element compositions and ratios, as well  
569 as isotopic ratios against stratigraphic position of the erupted products established  
570 according to geological and geochronological information (Rivera et al., 2016;  
571 Samaniego et al., 2016). During the growth of Ampato Basal edifice, andesitic and dacitic  
572 (57–65 wt.%  $\text{SiO}_2$ ) magmas were emitted. Later, during construction of the Ampato  
573 Upper edifice, volcanic products with a wide geochemical variability from andesites to  
574 dacites (57–69 wt.%  $\text{SiO}_2$ ) were erupted. In addition, the groups 2 and 3 dacites were  
575 emitted at roughly the same time (i.e. Ampato Upper edifice). During Sabancaya's

576 evolution, the SiO<sub>2</sub> content varies slightly between andesites and dacites (60–66 wt.%  
577 SiO<sub>2</sub>), but is relatively constant and similar to that of group 2 andesites and dacites of  
578 Ampato Upper edifice. In recent times, the geochemical composition of erupted magmas  
579 is roughly andesitic (57–63 wt.% SiO<sub>2</sub>). Trace element ratios (e.g., Sr/Y) as well as  
580 <sup>87</sup>Sr/<sup>86</sup>Sr, <sup>206</sup>Pb/<sup>204</sup>Pb, <sup>207</sup>Pb/<sup>204</sup>Pb and <sup>208</sup>Pb/<sup>204</sup>Pb ratios (Fig. 8) also have a wide  
581 compositional variation throughout the Ampato Basal edifice and predominantly  
582 homogeneous compositions throughout Sabancaya. It is worth noting that group 3 dacites  
583 have low Sr/Y values, but high <sup>87</sup>Sr/<sup>86</sup>Sr ratios, a pattern that contrasts with group 2  
584 dacites (high Sr/Y and high <sup>87</sup>Sr/<sup>86</sup>Sr ratios). Through its evolution, most differentiated  
585 products (mostly dacites) were erupted between 40 ka and 20 ka, however, the  
586 geochemical and isotopic signatures of these dacites (groups 2 and 3) suggest that the  
587 crustal process responsible for their petrogenesis are not the same. Lastly, we would stress  
588 that rhyolites display wide Pb isotopes values (*cf.* <sup>208</sup>Pb/<sup>204</sup>Pb), therefore based on this  
589 data and their trace elements behaviour (see above), we conclude that rhyolites (group 4)  
590 do not belong to the Ampato-Sabancaya magmatic series.

591

## 592 **6. Discussion**

### 593 **6.1. The sources of Ampato-Sabancaya magmas**

594 Previous studies suggest that the primitive magmas for volcanoes in Southern Peru  
595 essentially result from partial melting of mantle peridotite that was previously  
596 metasomatised by fluids released during dehydration of the subducting slab (Thorpe et  
597 al., 1984; Vatin-Pérignon et al., 1992; Thouret et al., 2005; Delacour et al., 2007; Mamani  
598 et al., 2010; Rivera et al., 2017; Huang et al., 2017; Samaniego et al., 2020). In the case  
599 of the ASCV magmas, their chemical and isotopic signatures point out to intermediate to  
600 differentiated compositions, precluding a purely mantle origin.



601           The source and evolution of magmas feeding the composite CVZ volcanoes has  
602 been extensively investigated whether on a regional (James, 1982; Barreiro and Clark, 1984;  
603 Hildreth and Moorbath, 1988; Davidson et al., 1991; Mamani et al., 2010; Blum-Oeste and  
604 Worner, 2016; Burns and de Silva, 2023) or single edifice scales (Davidson et al., 1990;  
605 Feeley and Sharp, 1995; Delacour et al., 2007; Sorensen and Holm, 2008; Thouret et al.,  
606 2005; Rivera et al., 2017; Samaniego et al., 2020). Because shallow differentiation  
607 processes affected magma composition, its mantle source is difficult to assess. For this  
608 reason, geochemists are interested for the scarce primitive compositions erupted in this arc  
609 segment. The Andahua-Huambo eruptive products display similar petrographic and  
610 geochemical characteristics than those of the other composite volcanoes, however they  
611 also display some key differences, namely the presence of olivine-rich, basaltic andesitic  
612 compositions ranking among the most primitive lavas erupted at the CVZ (Delacour et al.,  
613 2007). Among these characteristics, we can mention low silica contents (as low as 52 wt.%  
614 SiO<sub>2</sub>), relatively high MgO and Mg# values (2.02–7.33 wt.% MgO; Mg# 39.31–61.55),  
615 and unradiogenic isotopic ratios (0.7059–0.7069 <sup>87</sup>Sr/<sup>86</sup>Sr; 0.5123–0.5125 <sup>143</sup>Nd/<sup>144</sup>Nd;  
616 18.298–18.629 <sup>206</sup>Pb/<sup>204</sup>Pb; 15.558–15.601 <sup>207</sup>Pb/<sup>204</sup>Pb; 35.546–38.643 <sup>208</sup>Pb/<sup>204</sup>Pb). Thus,  
617 the Andahua-Huambo lavas represent a base-line magma composition in Southern Peru  
618 and provide a window to unravel the deep crustal processes active at the CVZ.

619           Petrological characteristics of the Andahua-Huambo magmas suggest that they  
620 evolved at deep reservoirs, being slightly modified at shallow levels in the crust. Indeed,  
621 the low HREE and Y contents, and high La/Yb and Sr/Y ratios, and the Sr, Nd-, Pb-, and  
622 O-isotope compositions of Andahua-Huambo lavas reveal that these magmas evolved at  
623 high pressure in the so-called MASH zone, whether by garnet-dominated AFC processes  
624 or lower crust partial melting leaving a garnet-bearing residue (Delacour et al., 2007;  
625 Sorensen and Holm, 2008; Huang et al., 2017).

626 In order to identify the arc magma sources of this part of the Andes, we followed  
627 the systematics proposed by Blum-Oeste and Wörner (2016), which suggest that CVZ  
628 magmas resulted from a mixture of a mantle-derived basaltic andesite (BA); an enriched  
629 basalt (EB); a crust-derived rhyodacite (RD) (Fig. 9). In a Sr vs. SiO<sub>2</sub> plot most ASCV  
630 compositions (at least the most primitive ones) fall inside the triangle formed by the  
631 previous end-members, and seems to define two different trends, the first one composed  
632 by the andesites and dacites of the groups 1 and 2; and the second defined by the group 3  
633 dacites. It is worth to note that SA 1033E sample, that represent the local mafic end-  
634 member for group 1 and group 2 fall relatively close to the mixing line formed between  
635 the two primitive end-members (BA and EB), whereas the intermediate and silica-rich  
636 compositions of groups 1 and 2 point to the high-silica end-member (RD). In contrast, the  
637 the group 3 dacites plot outside the previously defined triangle. In this diagram, Andahua-  
638 Huambo compositions define a trend with a break-in-slope around 57 wt.% SiO<sub>2</sub>. The  
639 andesitic and dacitic compositions tend to merge the ASCV trend, whereas the low-silica  
640 compositions fall along the BA-EB side, confirming the fact that primitive magmas in  
641 this part of the arc are not homogeneous. Based on this analysis, we propose that parental  
642 magmas for the group 1 and 2 should be different than that of the group 3.

643

## 644 **6.2. Intracrustal processes**

645 Ampato-Sabancaya magmas resulted from extensive crustal processing that  
646 include fractional crystallization, crustal assimilation, and magma mixing. We discuss the  
647 mineralogical and geochemical evidence for each of these processes.

648

### 649 *6.2.1. Fractional crystallization*

650 Several mineralogical and geochemical characteristics indicate that fractional  
651 crystallization (FC) played an important role during the evolution of Ampato-Sabancaya  
652 magmas. Among these characteristics are: (a) the presence of zoned plagioclase,  
653 clinopyroxene, and olivine phenocrysts; (b) the modal compositions of the main minerals  
654 that vary with magmatic differentiation; (c) the well-correlated trends between some  
655 incompatible elements (*e.g.*, Rb *versus* Th, [Fig. 10a](#)); and (d) the depletion in compatible  
656 elements (*e.g.*, Ni, Cr, Sr, Yb) along differentiation trends ([Fig. 4, 10b](#)). Trace element  
657 variations clearly indicate mineral fractionation, such as decreases in Ni and Cr with  
658 increasing silica contents which suggest olivine and clinopyroxene fractionation.  
659 Depletion in MREE and HREE usually indicate amphibole and/or garnet crystallization,  
660 whereas the negative trend observed in the MREE/HREE (*e.g.*, Dy/Yb) *vs.* SiO<sub>2</sub> diagram  
661 clearly suggests a leading role for amphibole fractionation ([Fig. 11a](#)). The decrease of Sr  
662 suggests plagioclase fractionation ([Fig. 4](#)), a process that is corroborated by the relatively  
663 weak negative Eu anomaly observed in most ASCV samples ([Fig. 5](#)).

664 To test our hypothesis that fractional crystallization occurred, we perform a two-  
665 step geochemical modelling procedure. First, major element mass-balance calculations  
666 ([Störmer and Nicholls, 1978](#)) between mafic and felsic end-members of the groups 1 and  
667 2 (SA-1033E and SA-1169A, respectively) allow us to estimate the modal composition  
668 of the cumulate (64-65% Pl + 18-23% Amp + 5-7 Bt + 2-4% Cpx + 5-6% Ti-Mag), as  
669 well as the degree of crystallisation (72%) required to evolve from a basaltic andesite to  
670 a dacite magma. It is noteworthy that the modal composition of the cumulate estimated  
671 from such calculations is similar to the observed mineral assemblage in ASCV eruptive  
672 products. Second, the calculated values are entered into the trace-element modelling  
673 equations of [Rayleigh \(1896\)](#) (details on mathematical procedures are given in [Janousek](#)  
674 [et al., 2015](#)). For the trace element modelling, we used the partition coefficients for

675 siliceous liquids of [Martin \(1987\)](#), [Rollinson \(1993\)](#), and [Bachmann et al. \(2005\)](#). We  
676 would stress that the geochemical modelling approach is challenging for highly porphyritic  
677 rocks (up to 30-40 vol.% crystals), which cannot be considered as true magmatic liquids  
678 following a liquid-line-of-descent. In addition, the geochemical dispersion observed in  
679 some diagrams such as Rb *versus* Ni ([Fig. 10b](#)) suggests that fractional crystallization  
680 alone cannot explain the observed geochemical diversity, indicating a more complex  
681 scenario. For example, in this geochemical space, the olivine-clinopyroxene-dominated  
682 fractional crystallization trend produces a noticeable decrease in Ni contents whereas Rb  
683 should be slightly increased. In addition, during fractional crystallization the ratio  
684 between two incompatible elements will not change drastically and samples related  
685 through fractional crystallization should define an approximately horizontal line if plotted  
686 against a fractionation index. This is not the case, as demonstrated by the K/Rb ratio  
687 which decreases with increasing Rb concentration ([Fig. 11b](#)). Thus, despite mineralogical  
688 and geochemical data suggesting an important role of fractional crystallization of a  
689 cumulate composed of plagioclase, pyroxenes, amphibole, and Fe-Ti oxides, other  
690 processes such as magma mixing and crustal assimilation must also be involved.

691

#### 692 *6.2.2. Assimilation-fractional crystallization (AFC)*

693 The ASCV data supports the hypothesis that crustal contamination played a key  
694 role in andesite and dacite magma genesis. The curved trend observed in K/Rb *vs.* Rb  
695 ([Fig. 11b](#)) demonstrates that Rb is more incompatible than K, a trend commonly present  
696 in other CVZ magmatic series and associated with AFC process ([Davidson et al., 1990](#)).  
697 In addition,  $^{87}\text{Sr}/^{86}\text{Sr}$  positively correlates to  $\text{SiO}_2$  content ([Fig. 6b](#)) while  $^{143}\text{Nd}/^{144}\text{Nd}$  is  
698 negatively correlated to  $\text{SiO}_2$  content in Ampato-Sabancaya samples (not shown). Such  
699 relationships are typical of crustal contamination ([Leeman and Hawkesworth, 1986](#);

700 DePaolo, 1981) and are widely documented in lavas throughout the CVZ (e.g., Thorpe et  
701 al., 1984; Hildreth and Moorbath, 1988; Davidson et al., 1991; Gerbe and Thouret, 2004;  
702 Delacour et al., 2007; Sørensen and Holm, 2008; Mamani et al., 2010; Godoy et al., 2014;  
703 Rivera et al., 2017). Additionally, Pb isotope ratios for Ampato-Sabancaya eruptive  
704 products ( $18.17 < ^{206}\text{Pb}/^{204}\text{Pb} < 18.49$ ;  $15.61 < ^{207}\text{Pb}/^{204}\text{Pb} < 15.63$ , and  
705  $38.55 < ^{208}\text{Pb}/^{204}\text{Pb} < 38.72$ ) point to those reported for the regional metamorphic basement  
706 (Barreiro and Clark, 1984; Mamani et al., 2008; Figs. 7a and b), providing evidence that  
707 the Ampato-Sabancaya magmas assimilated significant amounts of Arequipa Massif  
708 basement during their ascent.

709 Consequently, to account for isotopic and trace element constraints, we test  
710 alternative models combining fractional crystallization with the assimilation of wall-  
711 rocks surrounding the magma reservoirs (AFC, DePaolo, 1981) (curve 1, Fig. 12). The  
712 amount of assimilated material correlates to the quantity of magma that has crystallized  
713 through ascent and cooling. For AFC modelling, we use the same parameters as the FC  
714 model, varying fractionation/assimilation ratios ( $r = 0.2$ ), and the Precambrian Charcani  
715 gneiss to represent the local upper continental crust composition (Boily et al., 1989;  
716 Sorensen and Holm, 2008; Rivera et al., 2017; Samaniego et al., 2020). The modelling  
717 results for our AFC model are shown in Fig. 12. Using these parameters, we can  
718 reproduce the geochemical diversity of andesites and dacites of groups 1 and 2. We stress  
719 that group 3 dacites cannot be modeled because, as showed in a previous section (see Fig.  
720 9), the parental magmas of these dacites are different than that of the other ASCV  
721 magmas.

722

723 *6.2.3 Magma mixing*

724 A magma mixing process is also suggested by the frequent disequilibrium textures  
725 and chemical zoning patterns observed in ASCV rocks. For example, rocks emitted in the  
726 1990-1998 Sabancaya eruptions frequently have disequilibrium textures (*e.g.*, hybrid  
727 andesites with a mixed population of plagioclase phenocrysts). [Gerbe and Thouret \(2004\)](#)  
728 interpreted such features as evidence of mixing between andesitic and dacitic end-  
729 members during repeated injections of mafic magmas into the base of a ~6 km-deep  
730 reservoir. In general, we observe: (a) reversely zoned plagioclase phenocrysts with  
731 “wavy” dissolution surfaces between the core and rim, and Ca-rich overgrowth rims; (b)  
732 clinopyroxene, orthopyroxene, and amphibole phenocrysts have reverse zoning,  
733 particularly in the outermost rims; (c) high Mg# and Cr<sub>2</sub>O<sub>3</sub> contents in some  
734 clinopyroxene phenocrysts suggest that these minerals crystallized from more primitive  
735 magmas. (d) banding textures observed at in some units of Ampato (AM-II5) and  
736 Sabancaya, indicating that magma mixing and mingling must be taken into account when  
737 interpreting the diversity of Ampato-Sabancaya magmas.

738 A magma mixing scenario is additionally suggested by the positive and negative  
739 correlations of some trace elements against silica ([Fig. 4](#)), linear correlations among  
740 incompatible trace elements, hyperbola-like trends in diagrams of incompatible trace  
741 element ratios ([Clynne, 1999](#)), and the distribution of compatible *versus* incompatible  
742 elements (*e.g.*, Ni *vs.* Rb diagram, [Fig. 9b](#)). To identify the main process responsible for  
743 the geochemical diversity recorded by ASCV magmas, we follow the trace element  
744 systematics of [Langmuir et al. \(1978\)](#) and [Schiano et al. \(2010\)](#) which enable us to  
745 distinguish between partial melting, fractional crystallization, and mixing processes.  
746 Plotting Rb, an incompatible element, and V, a compatible element, in a Rb/V *versus* 1/V  
747 diagram, yields a linear trend for most samples ([Fig. 13](#)) that suggests a binary mixing  
748 process between a mafic mantle-derived end-member and a silica-rich end-member.

749 To test the magma mixing hypothesis in the ASCV series, we apply a trace  
750 element mass-balance mixing model with mafic and siliceous end-members using the  
751 equations of [Langmuir et al. \(1978\)](#). This model accurately describes the geochemical  
752 diversity of both magmatic series (curve 2, [Fig. 13](#)), and allows us to constrain both basic  
753 and silicic end-members. The basic end-member is represented by the most magnesian  
754 (group 1), mantle-derived magmas of the Ampato edifice (*e.g.*, SA-1033E). This mafic  
755 end-member is depleted in incompatible trace elements, such as LILE and LREE, and has  
756 low values for trace element ratios (*e.g.*, Th/La, La/Yb). In contrast, this end-member has  
757 high concentrations of most compatible elements such as HREE and the transition metals.  
758 The silicic end-member is represented by group 2 dacites (*i.e.*, SA-0914), which are  
759 characterized by enrichment in most incompatible elements, as well as low concentrations  
760 of compatible elements. Additionally, in the geochemical spaces represented in [Fig. 13](#),  
761 an extrapolation of the mixing model beyond the silicic end-member potentially leads to  
762 group 3 dacite compositions. We stress, however, that trace elements systematics ([Fig. 4](#))  
763 demonstrate that group 2 dacites are geochemically different from group 3 dacites,  
764 implying that two different “recipes” are needed to produce these distinct silica-rich  
765 magmas.

766

### 767 **6.3. The origin of Ampato dacites: different sources or different levels of** 768 **differentiation?**

769 As mentioned, Ampato dacites display two contrasting geochemical signatures.  
770 Group 2 dacites are characterized by depletion in HREE and Y, which yield high Sr/Y  
771 (50.91–60.50) and Dy/Yb (2.14–2.61) ratios ([Fig. 11a](#)). Additionally, they have high  
772  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.7068–0.7070),  $^{206}\text{Pb}/^{204}\text{Pb}$  (18.2098–18.2537),  $^{207}\text{Pb}/^{204}\text{Pb}$  (15.6136–  
773 15.6159), and  $^{208}\text{Pb}/^{204}\text{Pb}$  (38.5464–38.5791) ratios. In contrast, group 3 dacites have

774 particular geochemical and isotopic feature that differ from most Ampato-Sabancaya  
775 eruptive products. These dacites show high concentrations in HREE and Y compared to  
776 andesites and dacites from group 2, and as a result these dacites also yield very low Dy/Yb  
777 ratios (1.76–2.14, [Fig. 11a](#)). In addition, group 3 dacites yield very high Sr isotopic ratios  
778 (0.7074–0.7075).

779         The relatively low Yb and Y contents of most Ampato-Sabancaya andesites and  
780 dacites might have been acquired during the first stage of evolution in the lower crust  
781 through AFC processes involving garnet and/or amphibole from primitive mantle-derived  
782 parental magma (e.g., [Davidson et al., 1990, 1991](#); [Kay, 2002](#); [Haschke et al., 2006](#);  
783 [Sørensen and Holm, 2008](#); [Mamani et al., 2010](#)). Then, in a second step, amphibole-  
784 dominated, upper crustal AFC processes would be responsible for the formation of group  
785 2 andesites and dacites.

786         In contrast, the low Sr/Y and Dy/Yb ratios of group 3 dacites clearly indicate a  
787 magmatic evolution under conditions where garnet and/or amphibole are *not* stable  
788 mineralogical phases ([Taylor and McLennan, 1988](#); [Alonso-Pérez et al., 2009](#)). However,  
789 given that Sr and Pb isotopic ratios are high for both dacite groups, significant crustal  
790 contamination occurs. We propose that group 3 dacites formed at upper crustal levels,  
791 following an AFC process in which amphibole do not play a leading role. Thus, two  
792 contrasting processes are responsible for the origins of both dacite groups. These  
793 processes differ on the depth at which crustal contaminations occurs, with deeper levels  
794 for group 2 and shallow levels for group 3 ([Fig. 14](#)). This difference suggests that a  
795 complex magma plumbing system exists below the ASVC and implies that the  
796 voluminous explosive eruptions that produced the Corinta Plinian tephra-fall deposits of  
797 the group 3 dacites required the development of large upper crustal reservoirs. In addition,  
798 as mentioned before, the parental magmas of the group 3 dacites seems to be different of



799 that feeding the main ASCV plumbing system, which implies that these magmas by  
800 passed the deep crustal source and then they did not acquire the classical HREE-depleted  
801 garnet-signature of the other ASCV magmas.

802

## 803 **7. Conclusions**

804 During about the last 500 ky, Ampato-Sabancaya eruptive products have  
805 geochemical and isotopical variations that define three different geochemical groups: (1)  
806 a group of andesites corresponding to old eruptive products of Ampato Basal edifice and  
807 Ampato Upper edifice; (2) a group of andesites and dacites that represent the main  
808 magmatic series covering most eruptive products of Ampato and Sabancaya; and (3) a  
809 volumetrically minor group of dacites displaying a different geochemical signature  
810 (compared with group 2 dacites). On one hand, most eruptive products of Ampato and  
811 Sabancaya volcanoes (groups 1 and 2) follow a two-step differentiation model in which  
812 primitive mafic magmas generated by partial melting of the metasomatized mantle wedge  
813 rise and accumulate at lower crustal reservoirs, where they evolved by AFC processes  
814 involving garnet and/or amphibole. This step is responsible for the HREE depletion and  
815 highly radiogenic signature of ASCV magmas. Trace element and isotope concentrations  
816 suggest that the Precambrian Charcani gneiss is the most likely crustal contaminant. At  
817 upper crustal levels, magmatic evolution is dominated, on one hand by magma mixing  
818 between two end-members producing the most common andesites and dacites of group  
819 2. On the other hand, group 3 dacites seem to result of upper crust AFC process from  
820 primitive magmas different than that produced the main ASCV trend.

821

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832

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1083

#### 1084 **Table captions**

1085 Table 1. Selected whole-rock analyses from the Ampato-Sabancaya volcanic complex:  
1086 major (wt.%) and trace elements (ppm), and Sr, Nd, Pb isotopic ratios.

1087

1088 Table 2. Textural and mineralogical characteristics of Ampato-Sabancaya compound  
1089 volcano. Mineral assemblages for each petrographic type are reported (*Pl* plagioclase, *Ol*

1090 olivine, *Opx* orthopyroxene, *Cpx* clinopyroxene, *Amp* amphibole, *Bt* biotite, *Mag*  
1091 Magnetite, *Ap* Apatite). Mineral abbreviations after [Whitney and Evans \(2010\)](#).

1092

1093 Table 3. Summary of mineralogical characteristics of Ampato-Sabancaya rocks.

1094

1095 Fig. 1. (a) Map showing the locations of the South American volcanic zones: Northern  
1096 (NVZ), Central (CVZ), Southern (SVZ) and Austral (AVZ), modified after [Stern \(2004\)](#).  
1097 (b) Northernmost part of CVZ in southern Peru (modified after [Thouret et al., 2005](#)).  
1098 Ampato-Sabancaya compound volcano is in the middle of the Plio-Quaternary volcanic  
1099 range in southern Peru, ~70 km NW of the city of Arequipa. (c) View of the western flank  
1100 of Ampato and Sabancaya.

1101

1102 Fig. 2. Geological map of ASVC complex overlaid on a hillshade base map generated  
1103 from a Digital Elevation Model (modified after [Samaniego et al., 2016](#)). Sampling sites  
1104 for lavas and tephra analysed in this study are indicated by red dots. We also include the  
1105 age determinations available for this volcanic centre.

1106

1107 Fig. 3. Microphotographs of thin sections from Ampato-Sabancaya samples. (a) Andesite  
1108 (SA-1165) from Yanajaja stage showing a mineral assemblage composed of plagioclase,  
1109 clinopyroxene, amphibole, biotite, and Fe-Ti oxides. Note the thin black aureole around  
1110 the amphibole and biotite. (b) Dacite (SA-1159) from Ampato Upper showing a mineral  
1111 assemblage composed of plagioclase, amphibole, clinopyroxene, and Fe-Ti oxides. (c)  
1112 Dacite (SA-1155) from Ampato Upper showing a mineral assemblage composed of  
1113 plagioclase, clinopyroxene, amphibole, biotite, and Fe-Ti oxides. (d) Rhyolitic pumice  
1114 (SA-1142A) showing a mineral assemblage composed of plagioclase and biotite. (e)

1115 Dacitic pumice (SA-1127D) from the Corinta tephra-fall deposit composed of  
1116 plagioclase, clinopyroxene, and Fe-Ti oxides. (f) Disequilibrium textures in the andesite  
1117 (SA-0917) from Sabancaya showing a plagioclase phenocryst with an altered (sieve) rim  
1118 and a fresh overgrowth rim. Mineral abbreviations are the same as Table 2.

1119

1120 Fig. 4. Major and trace elements variation diagrams. Petrographic fields in the  $K_2O$  vs.  
1121  $SiO_2$  diagram after [Peccerillo and Taylor \(1976\)](#). All major elements (except  $K_2O$ ),  
1122 transition elements (e.g., Ni, Cr), Sr, Sm, Zr, and possibly Yb are negatively correlated  
1123 with  $SiO_2$ , while  $K_2O$ , Rb, and to some extent La are positively correlated. G1-4  
1124 correspond to the four groups identified (see text for more details).

1125

1126 Fig. 5. (a) Trace elements normalized to primitive mantle and (b) REE normalized to  
1127 chondritic values (both after [Sun and McDonough, 1989](#)) for rocks of the evolutionary  
1128 stages of ASCV. Brown area represents normalized composition of lavas and tephra  
1129 from the Early andesitic stage (Ampato Basal edifice), as well as to the scoriaceous  
1130 tephra-fall and pyroclastic-flow deposits of Ampato Upper edifice (Group 1). Green  
1131 area represents normalized composition of lavas from the Moldepampa stage, Ampato  
1132 Upper edifice, and Sabancaya edifice (Group 2). G1-4 correspond to the four groups  
1133 identified.

1134

1135 Fig. 6. (a)  $^{87}Sr/^{86}Sr$  vs.  $^{143}Nd/^{144}Nd$  diagram for Ampato-Sabancaya rocks, compared with  
1136 other published isotopic data for the CVZ, SVZ, and NVZ ([Davidson et al., 1991](#)). (b)  
1137  $SiO_2$  vs.  $^{87}Sr/^{86}Sr$  wt.% diagram. Insets depict the evolution of the isotopic composition  
1138 during fractional crystallization (FC), mixing, and assimilation-fractional crystallization  
1139 (AFC) processes. Symbols are the same as [Fig. 4](#).

1140

1141 Fig. 7. (a)  $^{208}\text{Pb}/^{204}\text{Pb}$  and (b)  $^{207}\text{Pb}/^{204}\text{Pb}$  vs.  $^{206}\text{Pb}/^{204}\text{Pb}$  diagrams of ASCV bulk rock  
1142 compositions. Compositional fields of Pb isotopic values for Andean volcanic zones are  
1143 from [Ancellin et al. \(2017\)](#). I= Isotopic fields of the southern Arequipa segment and  
1144 northern Toquepala segment; II= Isotopic fields of the northern Arequipa segment; III=  
1145 mafic and intermediate magmatic rocks of the Lima segment. In  $^{207}\text{Pb}/^{204}\text{Pb}$  and  
1146  $^{208}\text{Pb}/^{204}\text{Pb}$  vs.  $^{206}\text{Pb}/^{204}\text{Pb}$  diagram, Ampato-Sabancaya rocks plot in the isotopic field of the  
1147 southern part of Arequipa segment and northern Toquepala segment of the Peruvian  
1148 Coastal batholith. DMM is Depleted MORB Mantle ([Rehkamper and Hofmann, 1997](#)).  
1149 (c)  $^{208}\text{Pb}/^{204}\text{Pb}$  and (d)  $^{207}\text{Pb}/^{204}\text{Pb}$  vs.  $^{206}\text{Pb}/^{204}\text{Pb}$  diagram of ASCV have trends consistent  
1150 with assimilation in shallow crust and assimilation in deep crust (MASH processes). CG  
1151 is Charcani gneiss. Symbols are the same as [Fig. 4](#).

1152

1153 Fig. 8. Compositional changes of Ampato-Sabancaya's lavas and juvenile pyroclastic  
1154 products through time. The chronological axis is inverse-logarithmic to account for higher  
1155 sampling density and wider compositional range in young eruptive products.

1156

1157 Fig. 9. Sr vs.  $\text{SiO}_2$  contents for Ampato-Sabancaya rocks and Andahua-Huambo volcanic province  
1158 with the three end-member involved in the genesis for CVZ magmatism from [Blum-Oeste and](#)  
1159 [Wörner \(2016\)](#).

1160

1161 Fig. 10. Th and Ni vs. Rb diagrams for Ampato-Sabancaya whole-rock samples. The plot  
1162 Ni versus Rb display a large diversity of values which suggest a more complex scenario  
1163 than simply fractional crystallization (FC). Arrows depict the evolution of magmas

1164 composition during fractional crystallization (FC) and mixing processes. Symbols are the  
1165 same as Fig. 4.

1166

1167 Fig. 11. a) K/Rb vs. Rb diagram. Arrows illustrate differentiation by fractional  
1168 crystallization and AFC, binary mixing, and variable degrees of partial melting. The  
1169 curved trend of the Ampato-Sabancaya samples indicate that fractional crystallization  
1170 alone cannot explain the variation. b) Dy/Yb vs. SiO<sub>2</sub> wt.% diagram. The arrows show  
1171 the expected effects of garnet, amphibole, and plagioclase-pyroxene fractionation. Note  
1172 that amphibole is the only mineral able to efficiently fractionate MREE over HREE (i.e.,  
1173 Dy/Yb). Legend is given in Fig. 4.

1174

1175 Fig. 12. (a) <sup>87</sup>Sr/<sup>86</sup>Sr vs. Sr (ppm), (b) Y (ppm), and (c) Co (ppm) vs. <sup>87</sup>Sr/<sup>86</sup>Sr diagrams  
1176 showing the curves of two petrogenetic models (indicated by numbers in parentheses)  
1177 such as assimilation-fractional crystallization (AFC) and magma mixing for Ampato-  
1178 Sabancaya magmas. (1) AFC model showing the effects of contamination of sample SA-  
1179 1033E by the Charcani gneiss (James, 1982; Boily et al., 1990). AFC parameters are given  
1180 in the figure. Circles in the curves represent the remaining proportion of melt after  
1181 assimilation. Curves have been calculated according to DePaolo (1981). (2) Bulk mixing  
1182 models between a basic end-member (sample SA-1033E) and a silicic end-member  
1183 (sample SA-0914). Symbols are the same as Fig. 4.

1184

1185 Fig. 13. (a) Rb/V versus 1/V diagram for Ampato-Sabancaya wholerock samples. The  
1186 linear trend highlights a binary mixing process (Schiano et al., 2010). b) Plot of Rb versus  
1187 Rb/V for lavas from Ampato-Sabancaya illustrating mixing curves. A schematic  $C^I$  vs.  
1188  $C^I/C^C$  and  $1/C^C$  vs.  $C^I/C^C$  diagrams are also shown with curves illustrating melt



1189 compositions produced by mixing, fractional crystallization, and partial melting  
1190 processes. Symbols are the same as [Fig. 4](#).

1191

1192 Fig. 14. Schematic diagrams illustrating the two mechanisms for andesite and dacites  
1193 formation of Ampato-Sabancaya in the CVZ. (A) Mechanisms for andesite and dacites  
1194 formation of group 1 and 2. (B) Mechanisms for dacites formation of group 3 (modified  
1195 after [Burns and de Silva, 2023](#)).

1196

1197 SEM 1. Selected plagioclase, clinopyroxene, orthopyroxene, amphibole, biotite, olivine,  
1198 magnetite, and ilmenite compositions (in wt.%) from Ampato-Sabancaya compound  
1199 volcano lavas.

1200 SEM 2. Major element (wt.%), trace element (ppm), Sr, Nd and Pb isotopic ratios for the  
1201 Ampato-Sabancaya volcanic complex.

1202 SEM 3. a) Ab-An-Or ternary projections for Ampato-Sabancaya plagioclase. b) Mg/(Mg  
1203 + Fe<sup>2+</sup>) *versus* Si (a.p.f.u., atoms per formula unit) diagram for calcic amphibole  
1204 (nomenclature after [Leake et al., 1997](#)) showing that Ampato-Sabancaya amphiboles are  
1205 edenite-pargasite (with:  $Ca_B \geq 1.50$ ,  $(Na+K)_A \geq 0.50$  and  $Ti < 0.5$ ) and Magnesiohornblende-  
1206 tschermakite (with:  $Ca_B \geq 1.50$ ,  $(Na+K)_A < 0.50$  and  $Ca_A < 0.5$ ).

1207 SEM 4. Pyroxene compositions for Ampato-Sabancaya rocks. (a) En-Wo-Fs ternary  
1208 projections for pyroxene and (b) pyroxenes discriminated by Cr<sub>2</sub>O<sub>3</sub> and Mg# contents.

Fig. 1

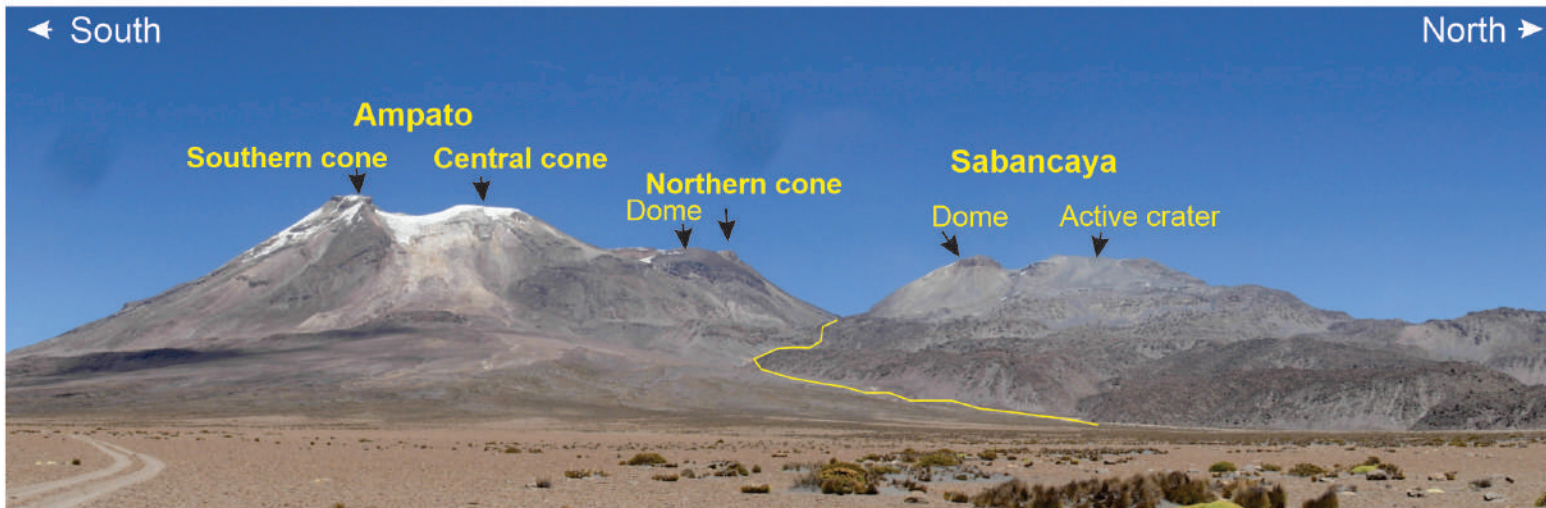
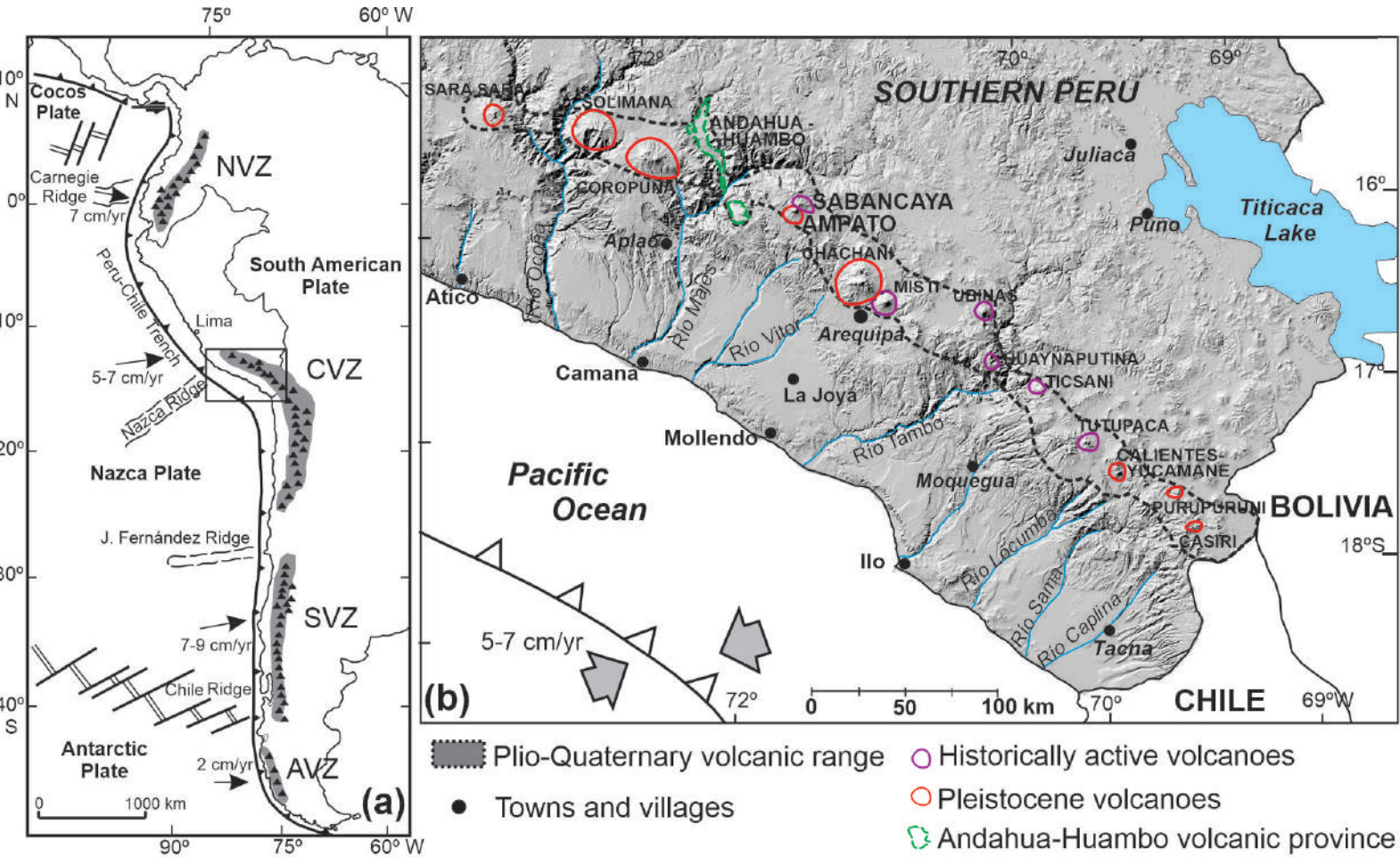




Fig. 2

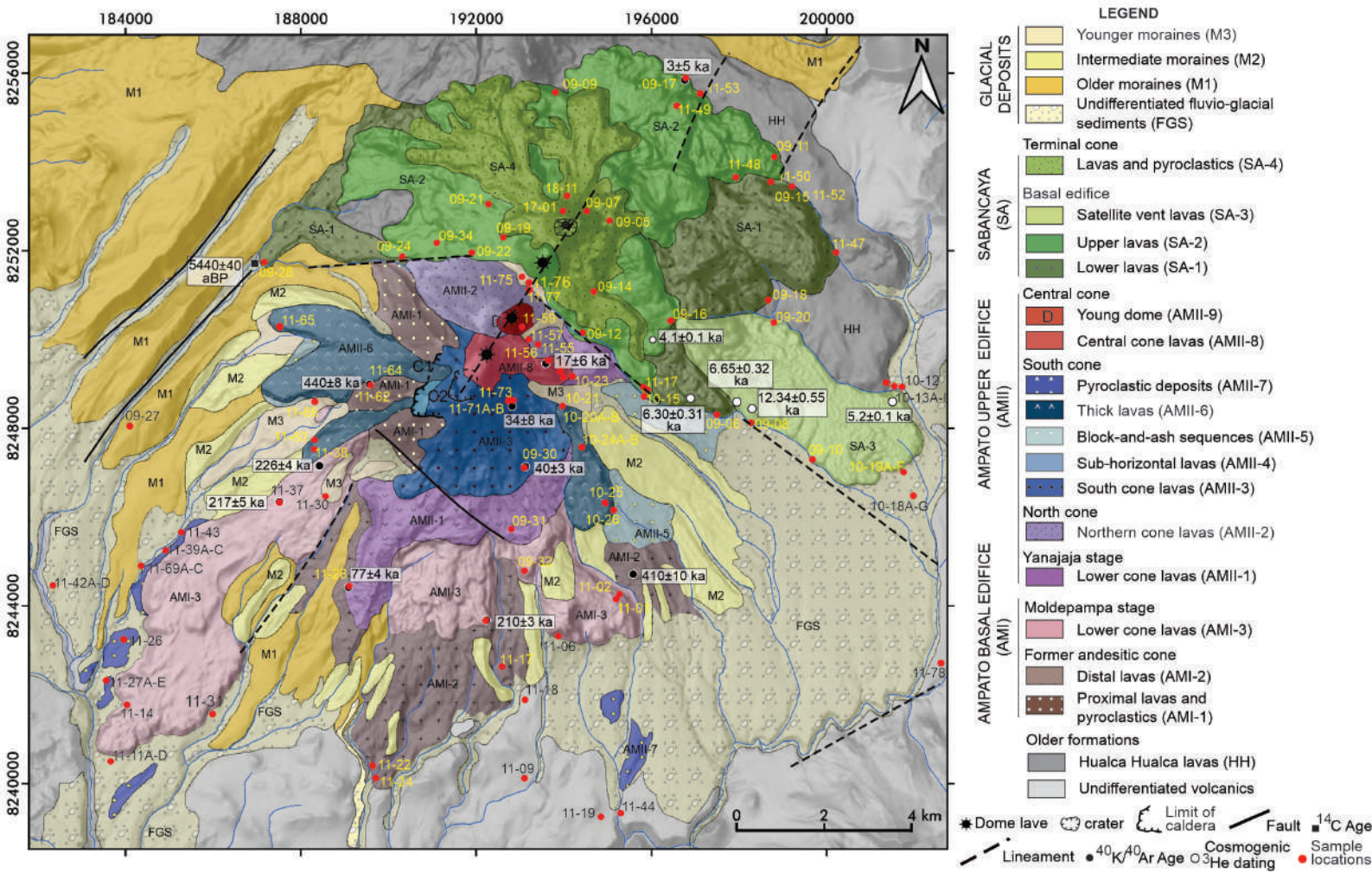
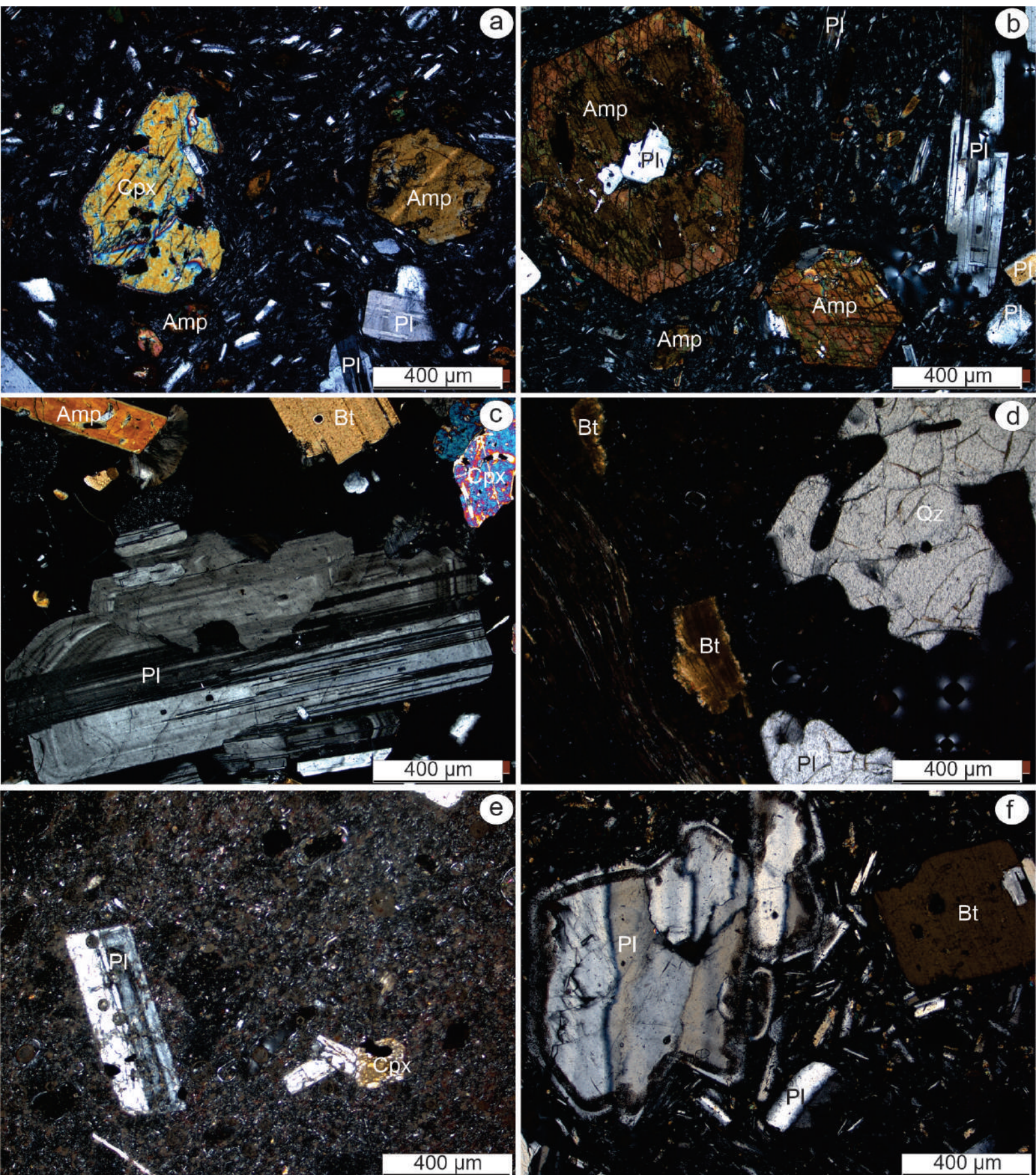




Fig. 3





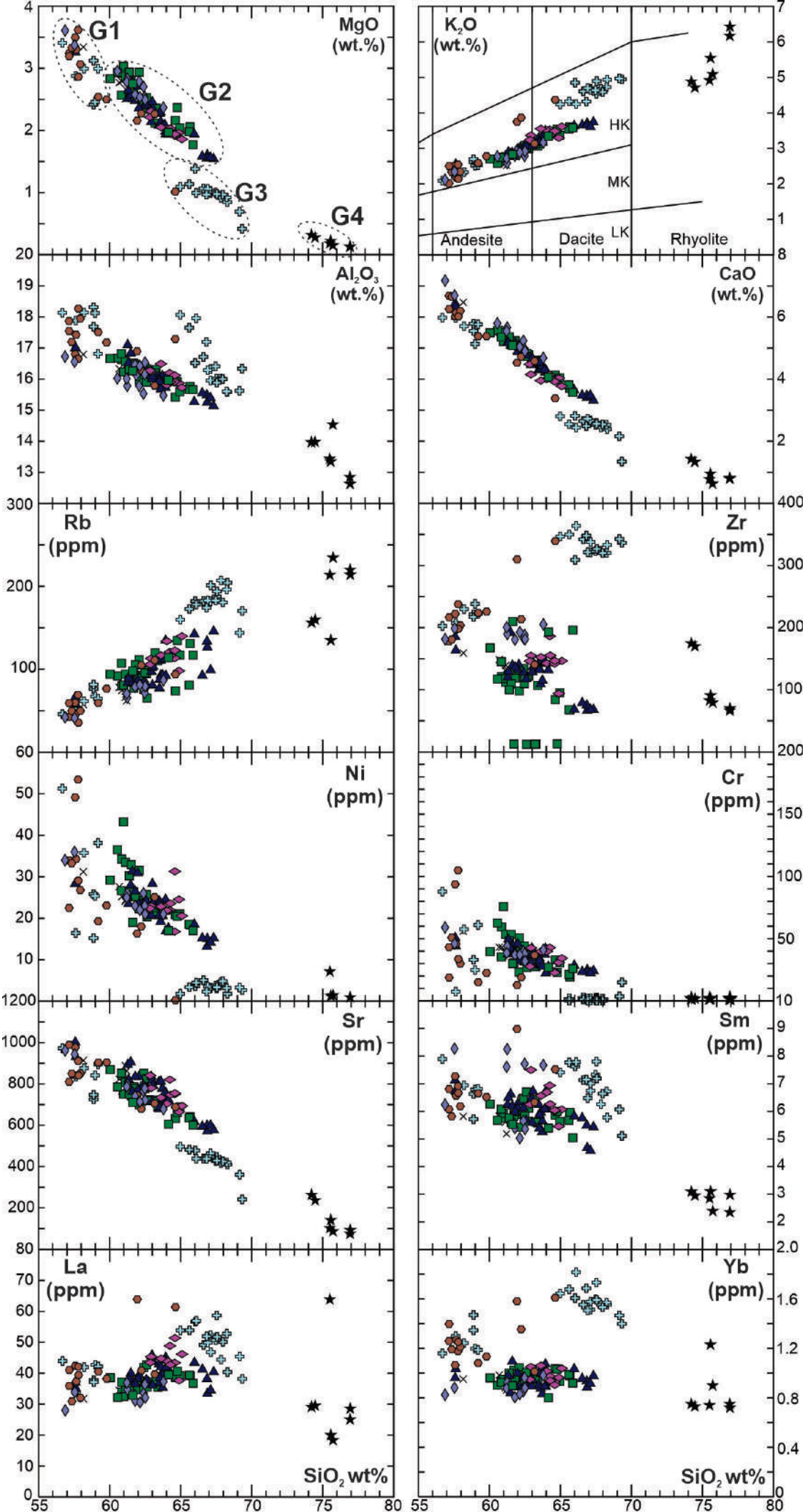


Fig. 4

Fig. 5

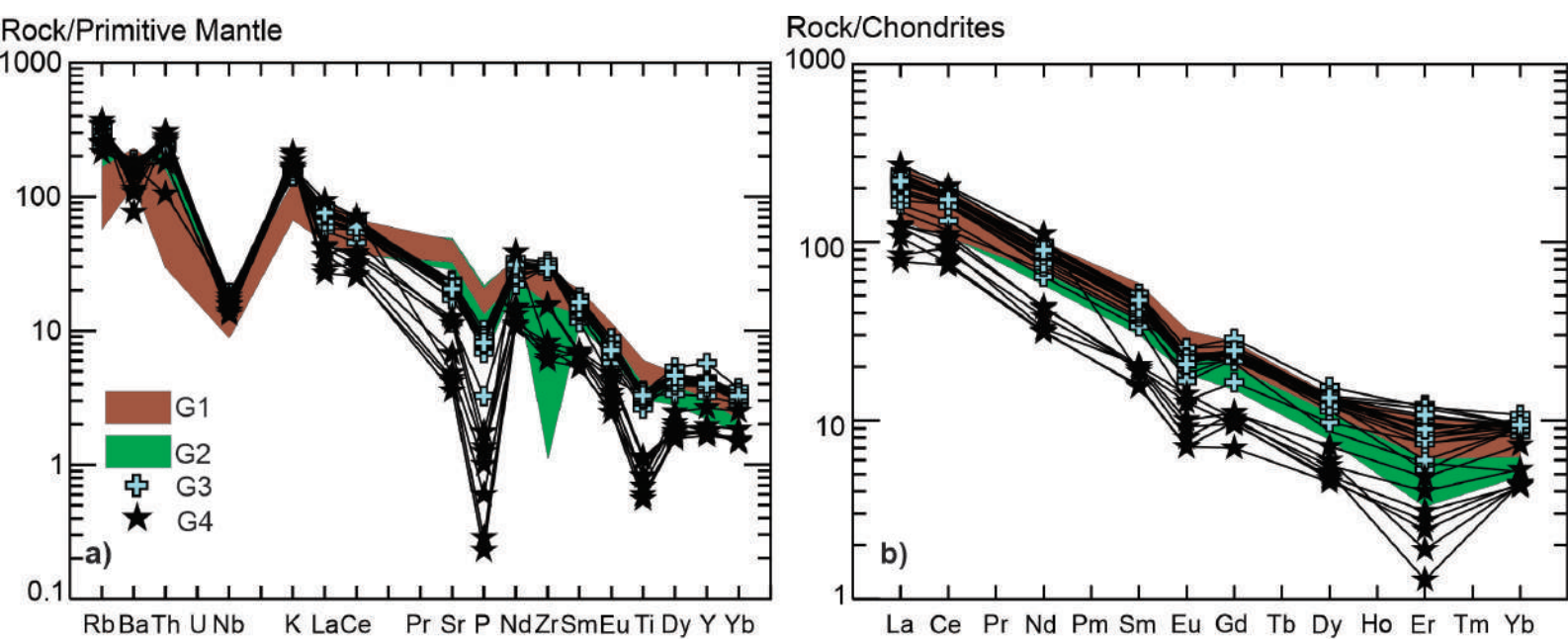


Fig. 6

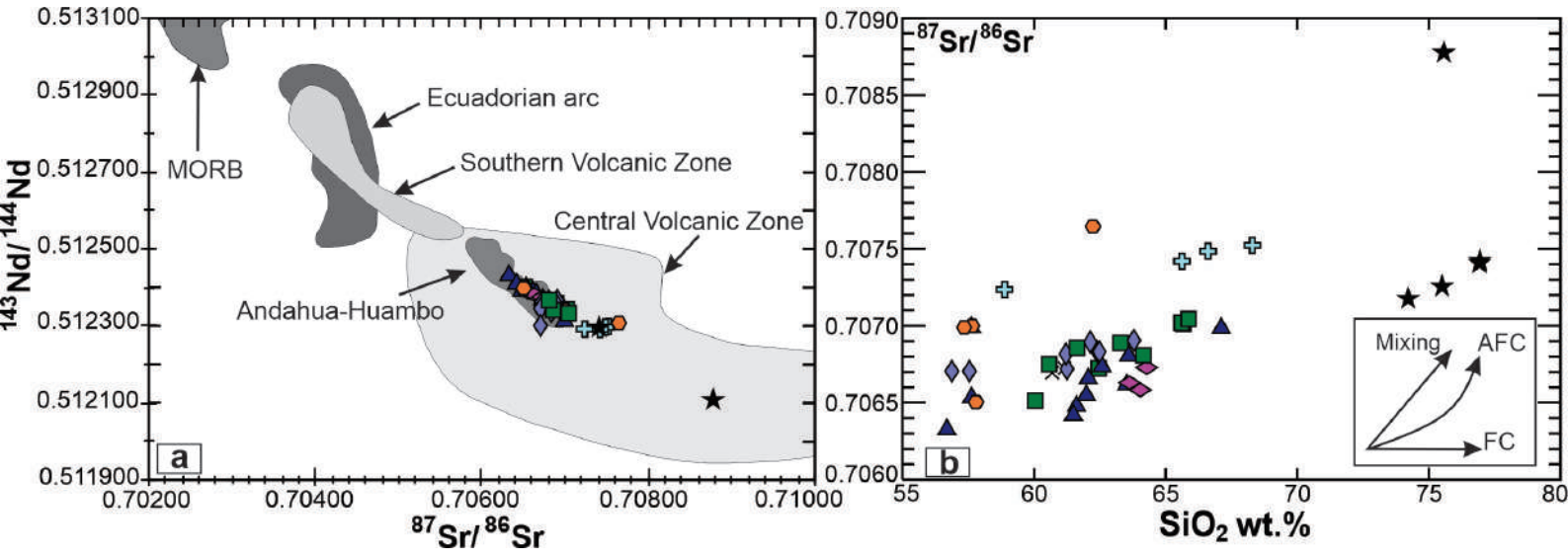


Fig. 7

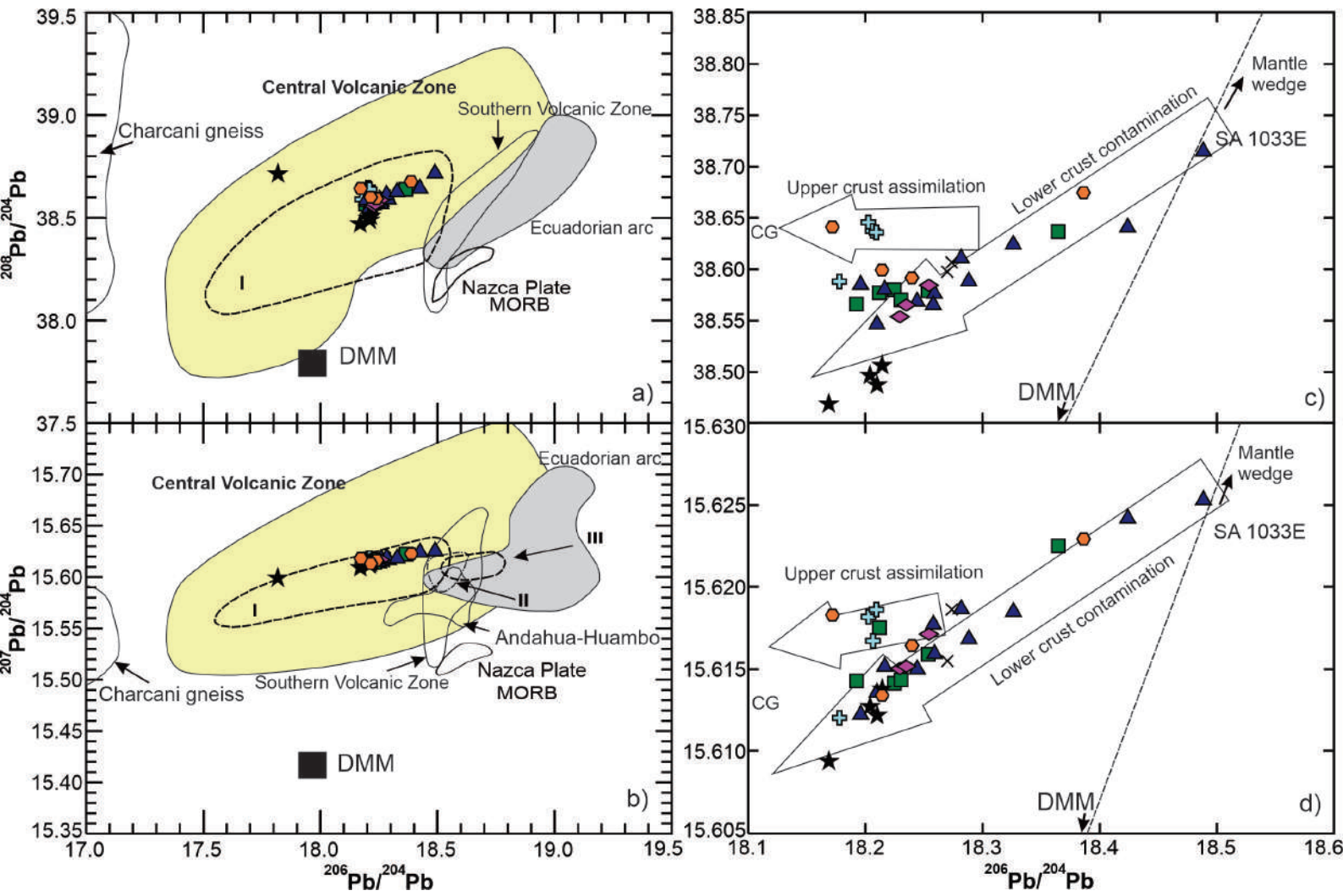




Fig. 8

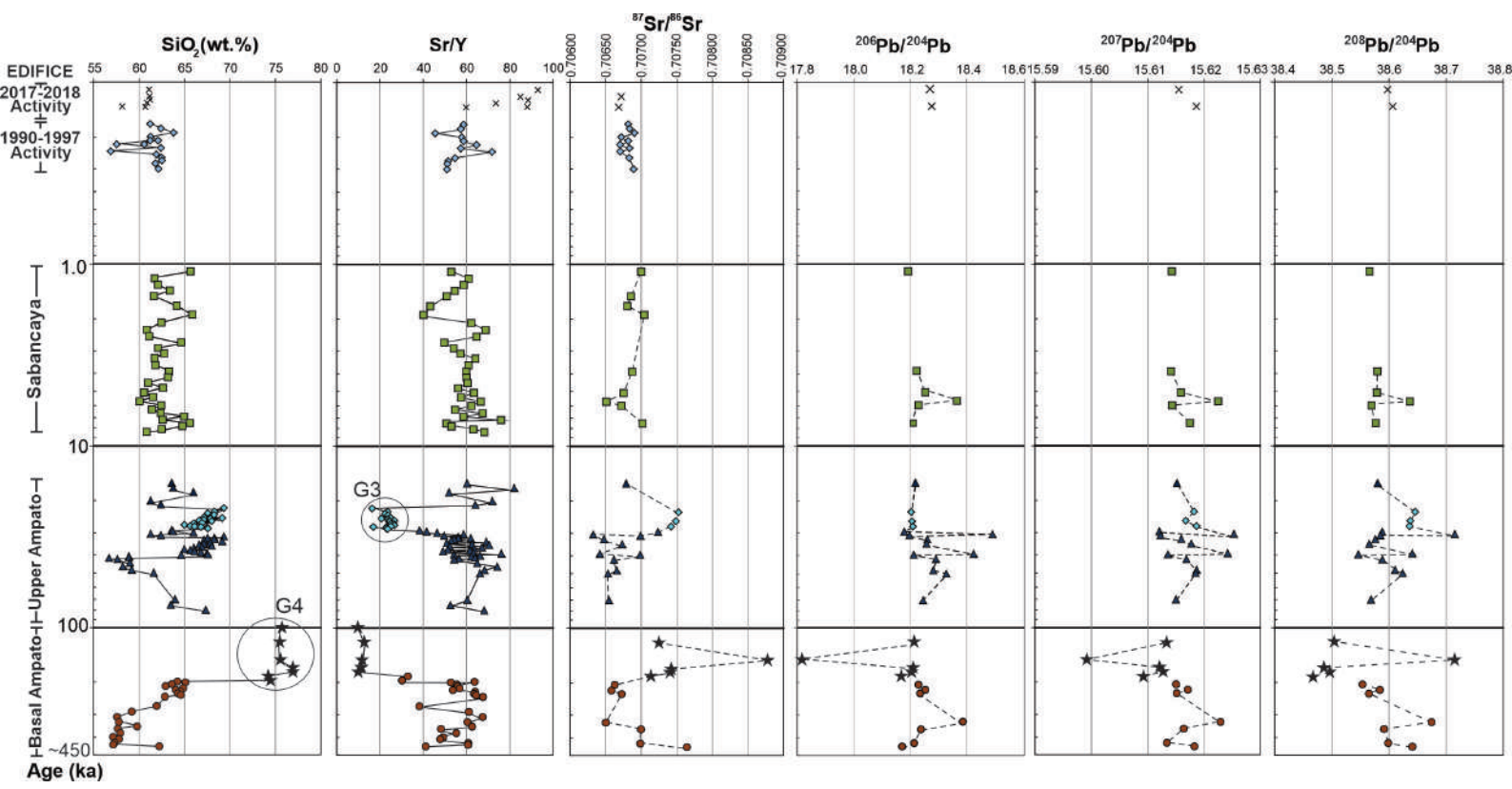
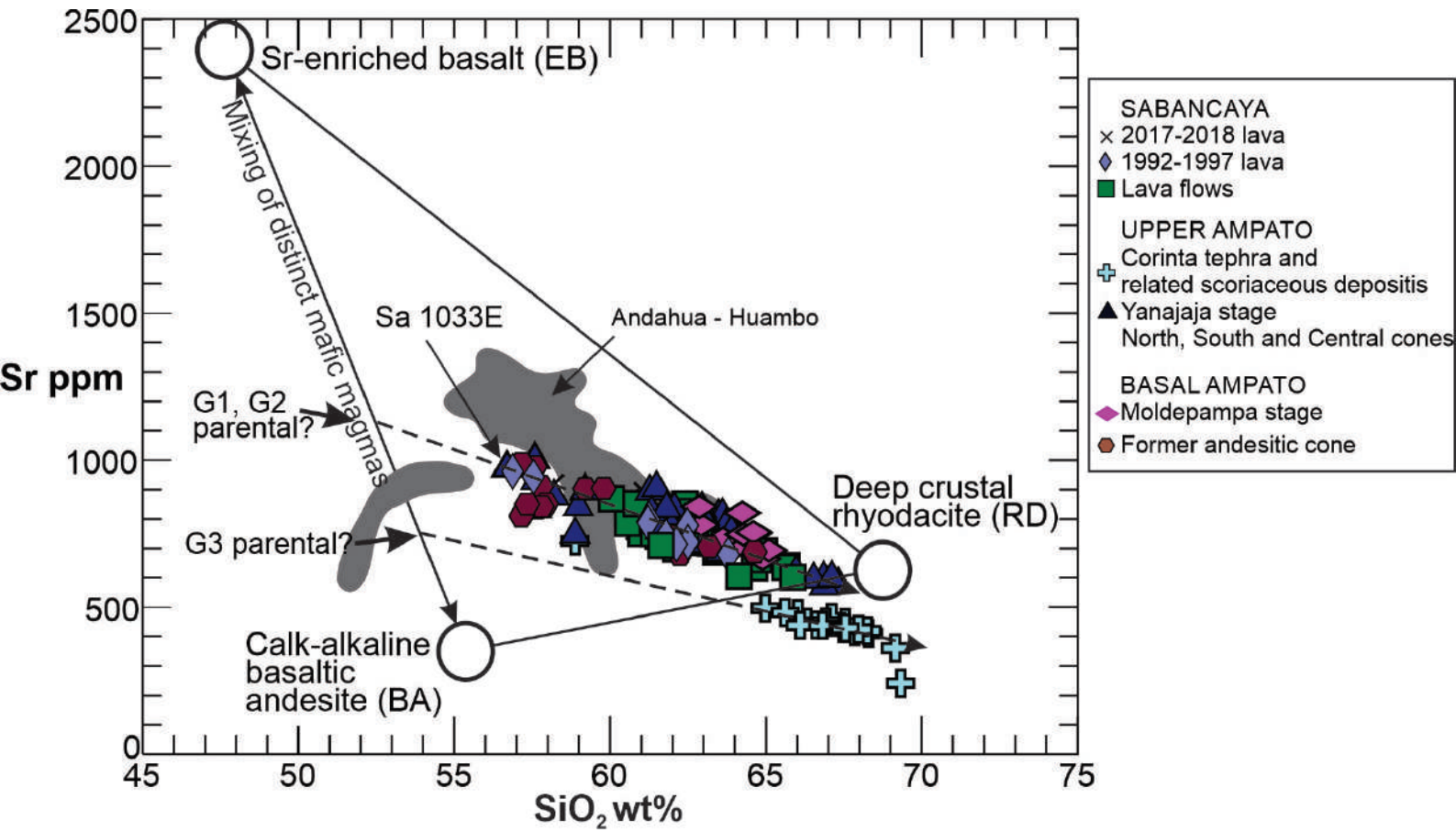


Fig. 9



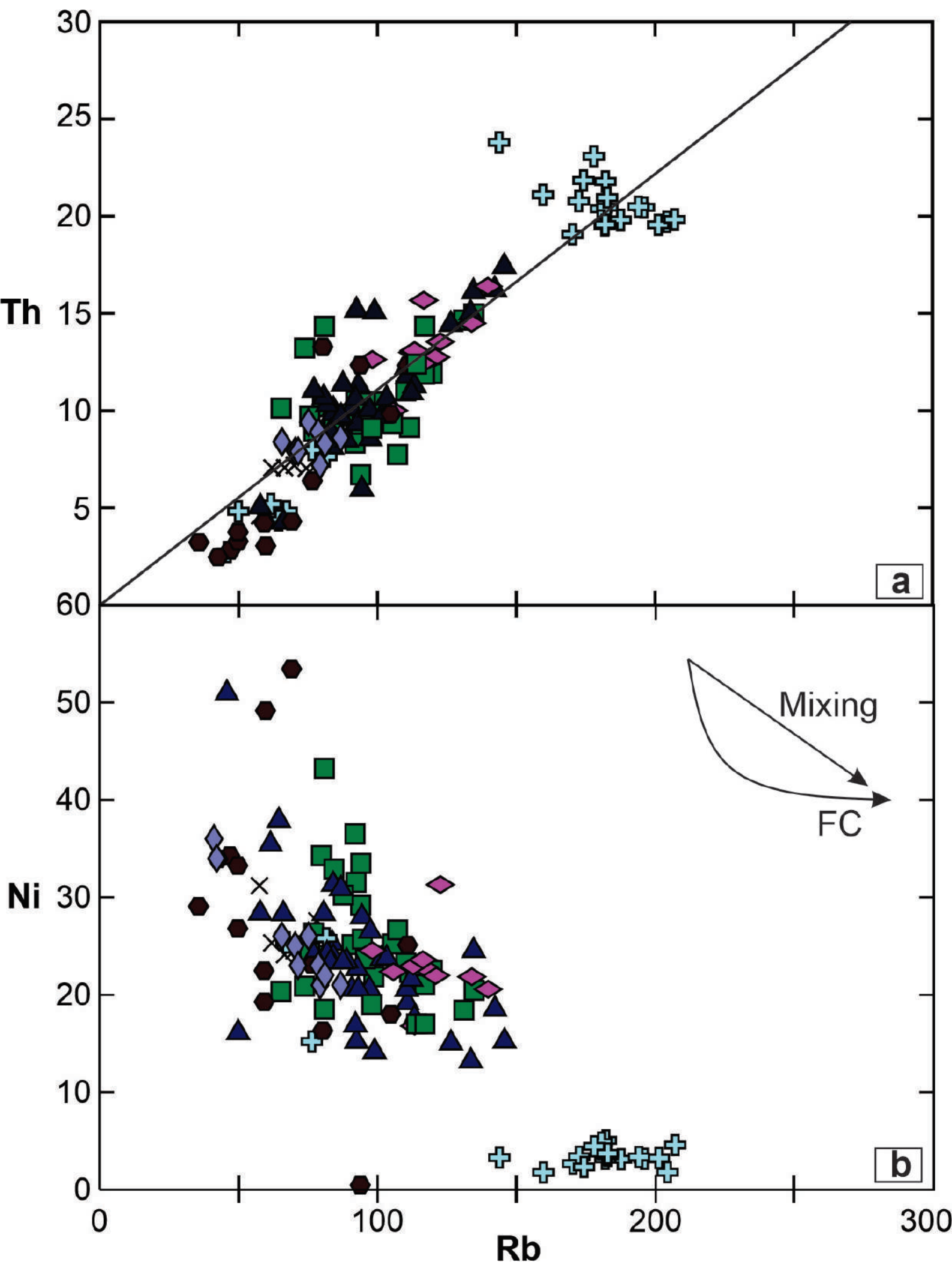


Fig. 10

Fig. 11

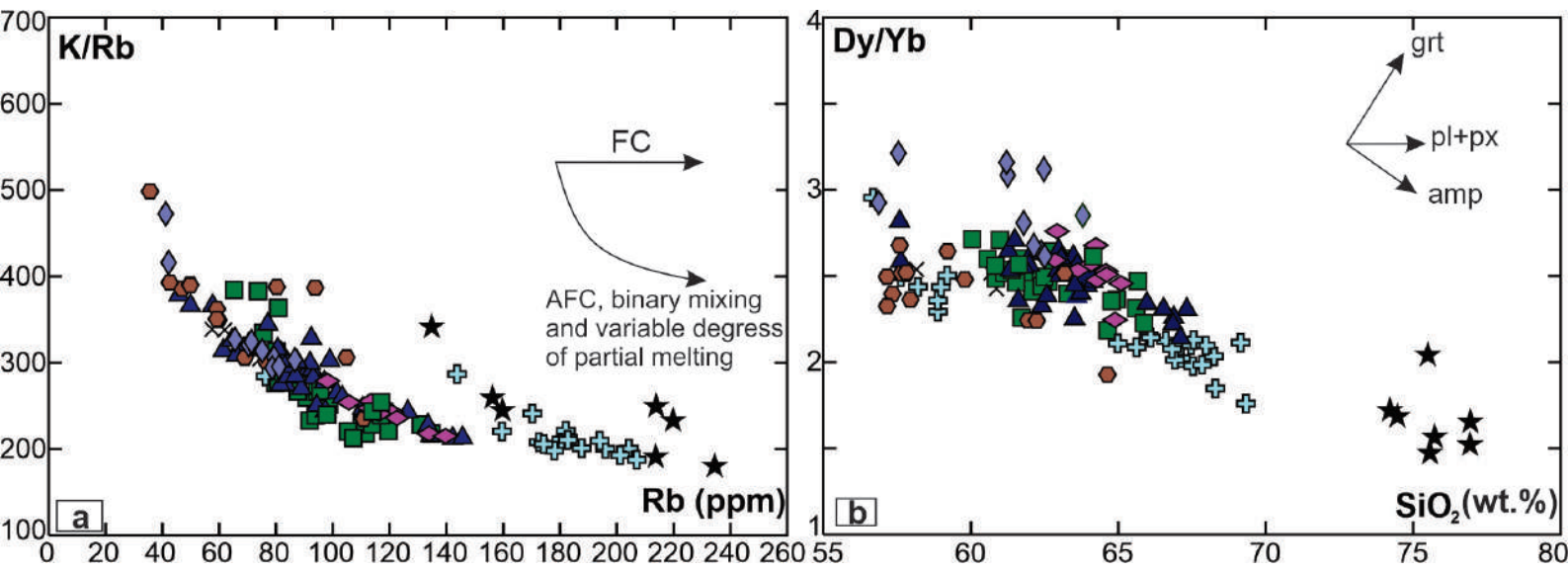
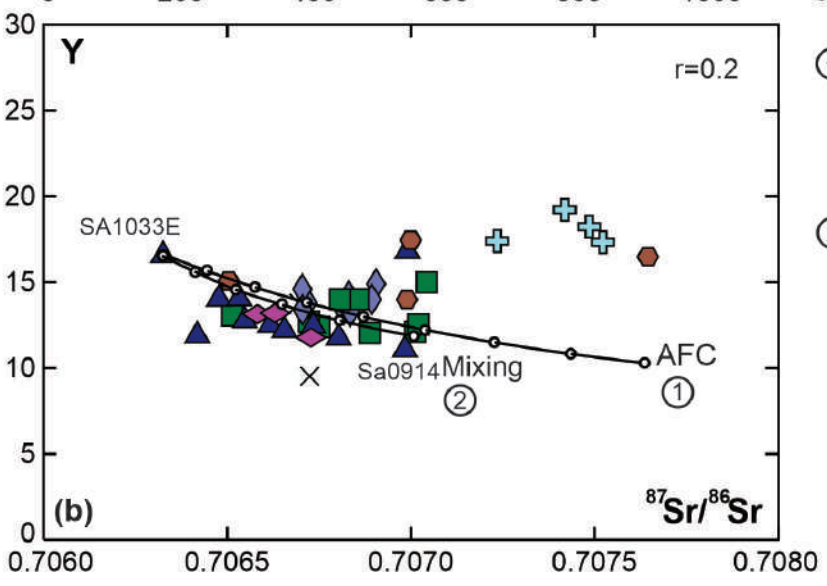
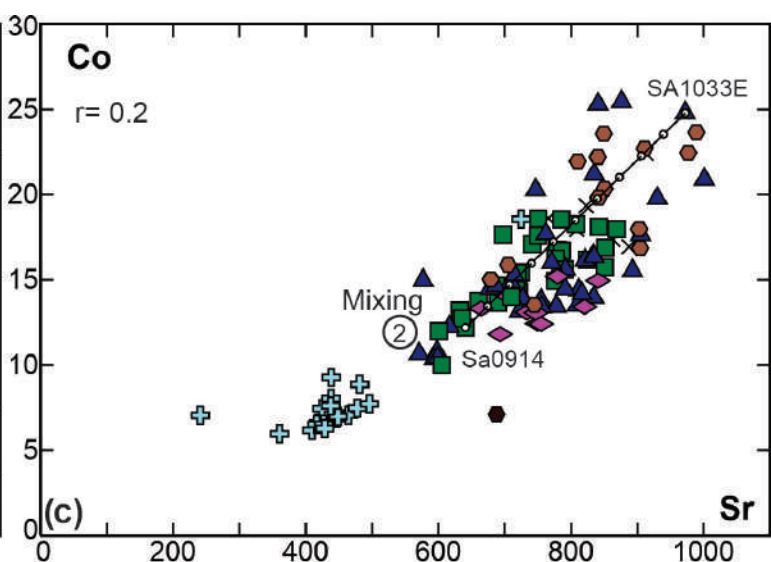
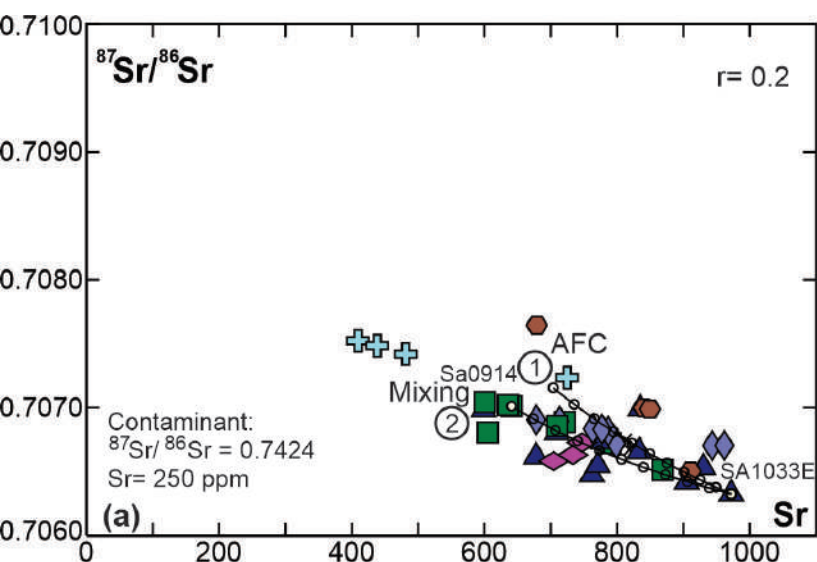


Fig. 12



- ① Curve of Assimilation - Fractional Crystallisation (AFC) with amphibole  
 $D_{\text{Sr}} = 1.31$   
 $D_{\text{Y}} = 2.48$   
 $D_{\text{Co}} = 4.25$
- ② Curve of magma mixing  
 Mafic magma SA 1033E : 56.7 wt.%  $\text{SiO}_2$   
 Felsic magma SA 0914 : 65.7 wt.%  $\text{SiO}_2$

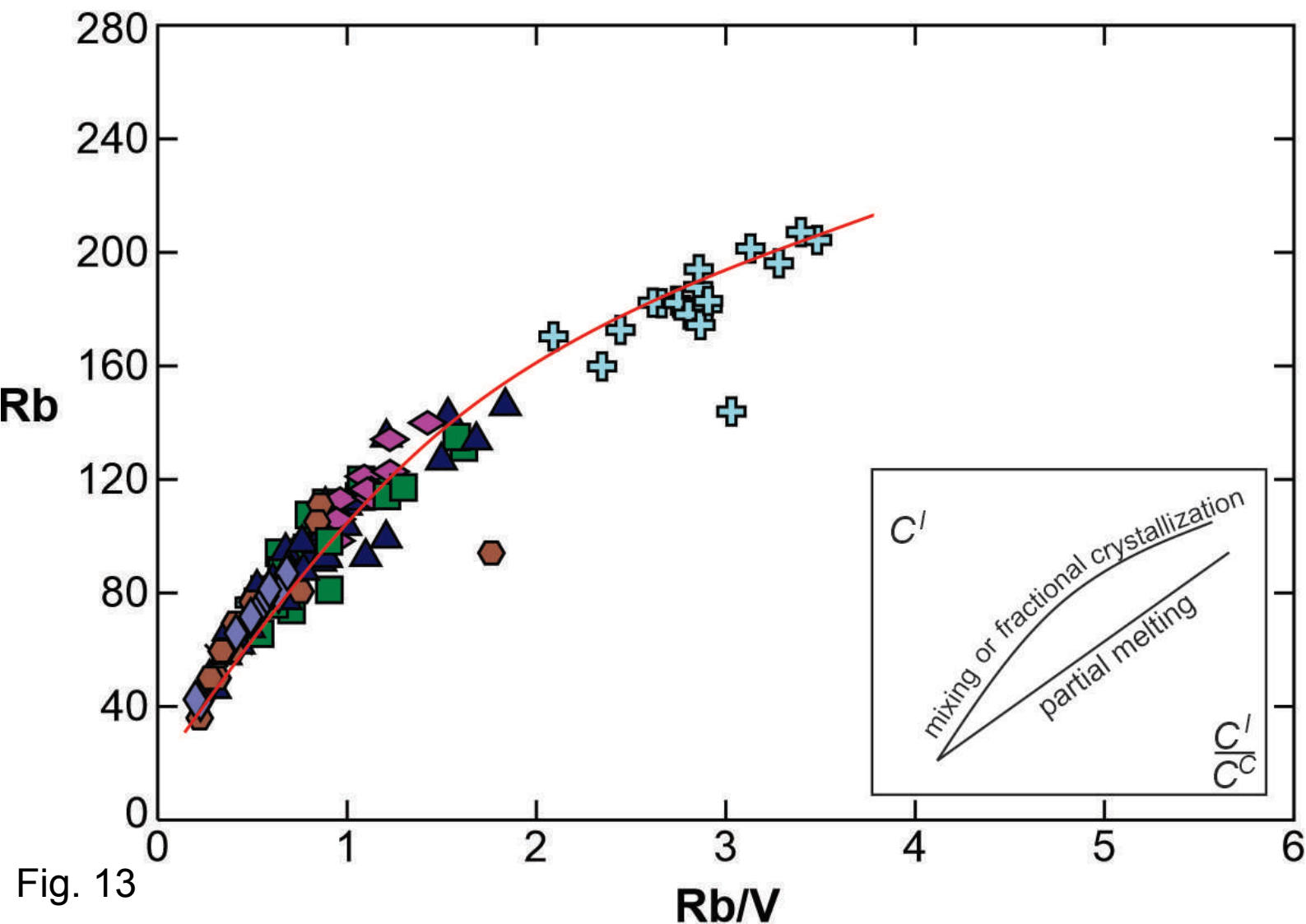
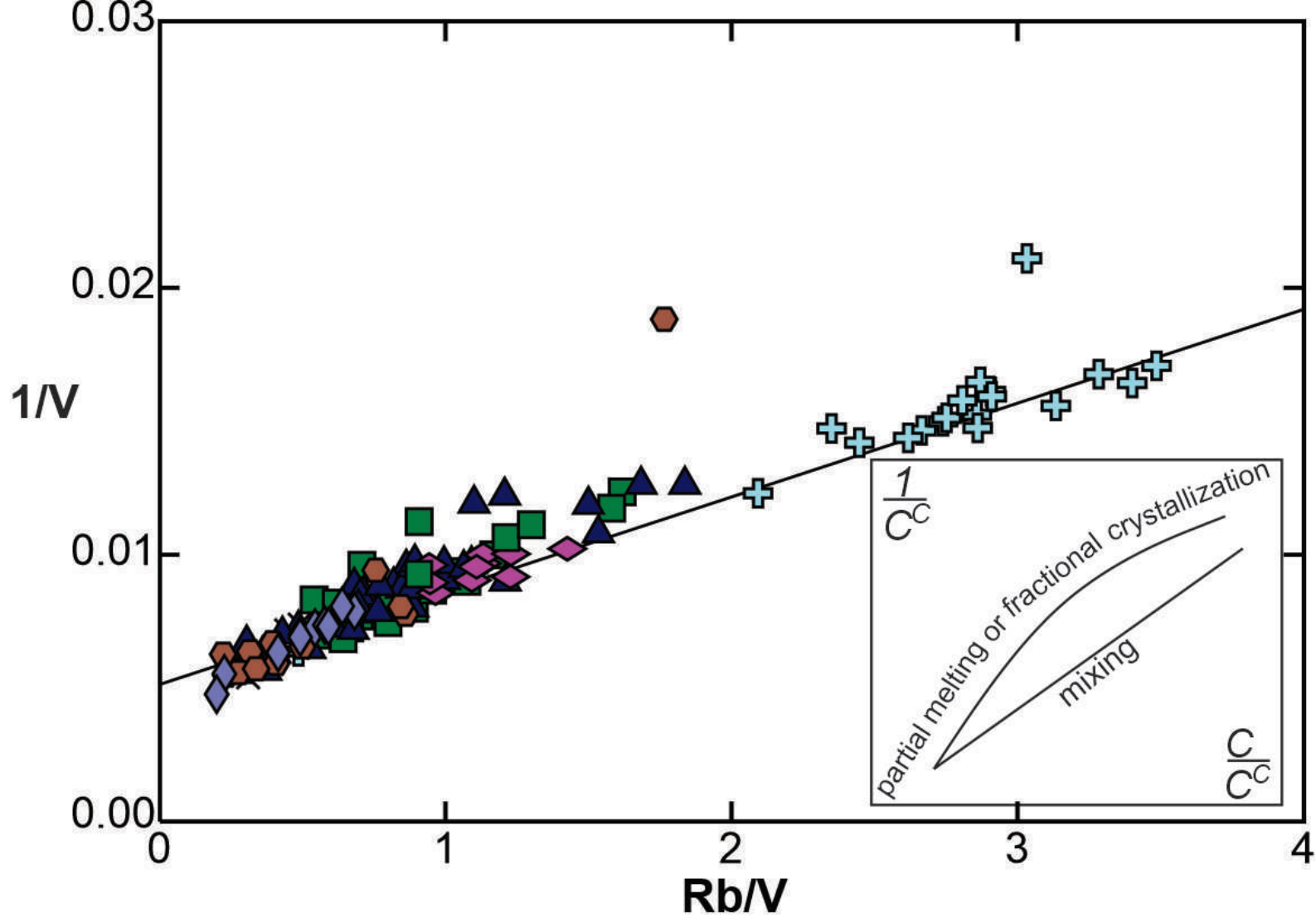


Fig. 13



Fig. 14

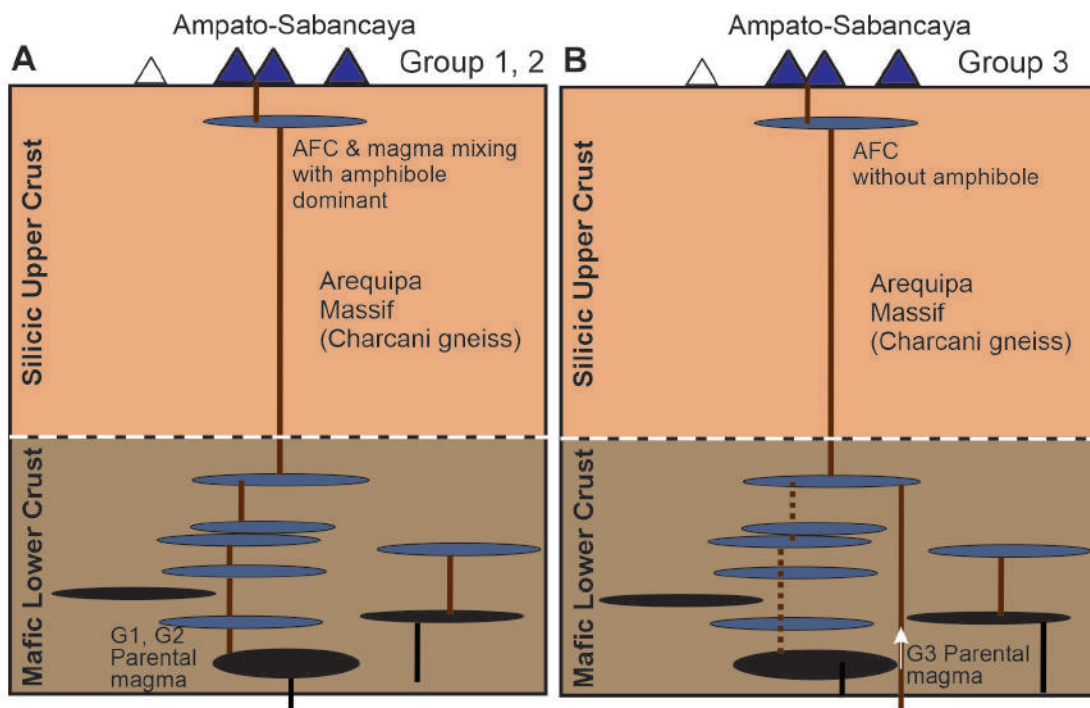


Table 1

Edifice	Ampato Basal				Ampato Upper									
	Former andesitic cone		Moldepampa		Rhyolitic sequence		Yanajaja	North Cone	South Cone			Scoriaceous tephra		Corinta tephra-fall deposit
Volcanic stage	G1	G2	G2	G2	G4	G4	G2	G2	G2	G2	G2	G1	G1	G3
Group	G1	G2	G2	G2	G4	G4	G2	G2	G2	G2	G2	G1	G1	G3
Sample	SA-1161	SA-1010	SA-1105	SA-0927	SA-1184A	SA-1184D	SA-0931	SA-1175B	SA-1176	SA-1016A	SA-1016C	SA-1033E	SA-1119	SA-1139A
UTM-North	8,249,025	8,248,399	8,243,190	8,247,869	8,234,467	8,234,467	8,245,728	8,251,299	8,251,058	8,248,912	8,248,912	8,237,181	8,239,566	8,245,165
UTM-East	189,617	201,368	194,897	184,099	809,521	809,521	192,947	193,121	193,196	195,902	195,902	190,762	195,040	184,842
Rock type	Lava flow	Lava flow	Lava flow	Lava flow	Tephra-fall deposit	Tephra-fall deposit	Lava flow	Lava flow	Lava flow	Scoria flow	Scoria flow	Scoria	Scoria flow	Tephra-fall deposit
Major oxide (wt.%)														
SiO <sub>2</sub>	56.43	60.53	63.4	61.94	70.62	71.71	62.00	57.04	61.48	59.6	65.4	53.4	57.7	61.8
TiO <sub>2</sub>	1.10	0.83	0.82	0.91	0.16	0.11	0.83	1.23	0.96	1.07	0.63	1.22	1.02	0.71
Al <sub>2</sub> O <sub>3</sub>	16.92	16.51	15.7	16.03	12.47	11.97	15.54	16.84	16.25	16.3	15.0	17.1	17.9	16.6
Fe <sub>2</sub> O <sub>3</sub>	7.34	5.27	4.77	5.01	0.98	0.62	5.03	7.25	5.54	6.03	3.84	7.43	6.80	4.02
MnO	0.10	0.08	0.06	0.06	0.08	0.04	0.07	0.08	0.07	0.07	0.05	0.10	0.09	0.05
MgO	3.28	2.11	2.00	2.18	0.21	0.12	2.23	3.23	2.33	2.49	1.52	3.21	2.37	1.07
CaO	6.54	4.4	3.97	4.41	0.89	0.74	4.43	6.38	4.83	4.92	3.39	5.63	5.44	2.40
Na <sub>2</sub> O	4.04	4.0	4.28	4.47	2.84	2.16	4.09	4.11	4.32	3.27	3.96	3.76	3.79	3.24
K <sub>2</sub> O	2.30	3.7	3.33	3.19	5.18	5.75	3.10	2.44	2.93	2.76	3.51	1.97	2.56	4.07
P <sub>2</sub> O <sub>5</sub>	0.36	0.3	0.31	0.33	0.03	0.00	0.28	0.45	0.35	0.39	0.13	0.41	0.30	0.19
LOI	0.5	1.0	0.77	0.36	4.71	4.81	1.45	0.5	0.25	0.50	2.41	4.94	2.02	4.39
TOTAL	98.94	98.7	99.46	98.89	98.16	98.02	99.04	99.57	99.30	97.40	99.80	99.21	99.98	98.52
Trace elements (ppm)														
Rb	49.8	80.3	116	105.7	134.8	219.8	87.5	66.1	83.1	94.4	99.0	46	76	173
Sr	849.7	744.5	747	840.7	140.9	74.6	686.6	1001.2	833.6	905.1	599.1	972	725	481
Ba	920.1	1589.0	1129	1155.1	1173.8	530.8	1001.1	1009.9	1083.6	1008.9	920.8	1132	1026	1222
Sc	11.8	9.9	8.0	8.6	2.6	2.5	9.3	12.1	8.8	9.1	7.1	12.9	13.1	6.4
V	179.4	106.2	105	111.7	5.6	4.7	113.5	177.4	118.4	139.4	81.9	150	157	70
Cr	50.8	12.7	25.0	27.7	1.7	1.5	32.3	50.6	32.5	41.9	22.4	87.7	33.0	0.2
Co	23.6	13.5	13.1	15.0	0.3	0.3	14.6	20.9	16.4	17.6	10.4	24.8	18.6	8.9
Ni	33.3	16.3	23.6	22.4	1.2	0.9	23.4	28.3	23.3	28.0	14.2	51.3	15.2	3.4
Y	14.0	19.5	11.8	12.4	12.0	7.4	13.1	13.5	12.2	11.9	11.1	16.6	17.4	19.2
Zr	180.8	309.7	155	146.1	90.9	66.5	132.0	185.2	140.1	191.8	67.8	203	221	350
Nb	6.7	12.6	8.9	9.5	12.8	10.9	7.8	8.3	9.6	9.0	8.6	8.3	8.1	12.7
La	30.90	63.9	43	45.2	20.0	25.0	38.4	37.0	39.4	40.0	34.5	44	38	54
Ce	64.74	119.3	87	89.8	56.4	46.2	77.8	80.4	82.4	80.7	66.4	87	78	113
Nd	32.18	45.9	36	38.5	15.2	14.7	32.9	38.5	35.5	36.9	26.7	45	36	43
Sm	5.82	9.0	6.3	6.2	3.1	2.4	5.9	7.1	6.3	6.6	4.6	7.9	6.6	7.8
Eu	1.53	1.8	1.36	1.5	0.6	0.4	1.3	1.7	1.6	1.6	1.0	1.86	1.57	1.30
Gd	4.16	5.4	4.2	4.3	2.3	1.4	3.9	4.9	4.1	4.2	3.0	5.6	4.9	5.1
Dy	2.85	3.5	2.3	2.5	1.8	1.1	2.5	2.7	2.3	2.3	2.0	3.4	3.4	3.5
Er	1.35	1.6	0.9	1.0	0.8	0.5	1.2	1.2	0.9	0.9	0.7	1.5	1.6	1.3
Yb	1.19	1.6	0.94	0.9	1.2	0.7	1.0	1.0	0.9	0.8	0.9	1.16	1.47	1.68
Th	3.75	13.3	12.4	10.0	8.8	23.8	11.3	4.3	8.9	6.0	15.1	2.7	8.0	20.8
<sup>87</sup> Sr/ <sup>86</sup> Sr	0.706989		0.706728		0.708776	0.707407	0.706548	0.707523	0.706656	0.706418	0.706989	0.706325	0.707235	0.707419



$\pm 2\sigma$ error	0.000007	0.000007	0.000007	0.000009	0.000006	0.000006	0.000006	0.000005	0.000006	0.000006	0.000008	0.000007
$^{143}\text{Nd}/^{144}\text{Nd}$	0.512342	0.512375	0.512108	0.512296	0.512394	0.512299	0.512383	0.512409	0.512343	0.512431	0.512292	0.512291
$\pm 2\sigma$ error	0.000022	0.000004	0.000007	0.000003	0.000005	0.000004	0.000004	0.000007	0.000005	0.000006	0.000005	0.000006
$^{206}\text{Pb}_{-204}\text{Pb}$	18.214174	18.234976	17.816697	18.203983	18.252469		18.281801	18.4239471	18.209770	18.4885391	18.177839	18.209318
$\pm 2\sigma$ error	0.0006	0.0004	0.0006	0.0007			0.0007	0.0006	0.0008	0.0006	0.0006	0.0007
$^{207}\text{Pb}_{-204}\text{Pb}$	15.613417	15.615174	15.599191	15.612741	15.61723		15.618665	15.6241859	15.613583	15.6253023	15.612039	15.618626
$\pm 2\sigma$ error	0.0006	0.0004	0.0006	0.0008			0.0006	0.0006	0.0007	0.0006	0.0005	0.0006
$^{208}\text{Pb}_{-204}\text{Pb}$	38.599166	38.565258	38.714973	38.496811	38.58141		38.610682	38.6407370	38.546364	38.7149278	38.588029	38.635910
$\pm 2\sigma$ error	0.0015	0.001	0.0018	0.002			0.0018	0.0015	0.002	0.0015	0.0015	0.0017

**Sabancaya**

Central Cone		Basal Sabancaya		Terminal Cone		2017-2018 Activity	
G3	G2	G2	G2	G2	G2	G2	G2
SA-1126	SA-1159	SA-0915	SA-0934	SA-0907	SA-0919	SA-1701	SA-1811
8,243,053	8,250,248	8,253,513	8,252,006	8,252,810	8,252,245	8252130	8252221
183,819	192,988	199,052	191,086	194,470	192,587	194412	194322
Bomb	Dome	Lava flow	Lava flow	Lava flow	Lava flow	Juvenile bomb	Juvenile bomb
65.2	62.5	64.9	59.65	61.1	62.5	60.2	61.18
0.60	0.86	0.73	1.07	0.95	0.87	1.00	0.95
14.9	15.597	15.5	16.55	16.3	15.8	16.2	16.44
3.29	5.02	4.17	6.23	5.63	5.15	6.2	5.89
0.05	0.07	0.06	0.08	0.07	0.07	0.076	0.08
0.88	2.25	1.96	2.81	2.51	2.26	2.74	2.66
2.41	4.36	3.77	5.45	5.04	4.54	5.46	5.48
3.53	4.131	4.12	4.43	4.20	4.14	4.34	4.35
4.52	3.17	3.50	2.68	2.85	3.03	2.63	2.67
0.16	0.30	0.23	0.38	0.30	0.27	0.337	0.33
2.78	1.03	0.52	0.24	0.15	0.25	0.09	0.10
98.36	99.25	99.48	99.59	99.16	98.84	99.22	100.13
196	110.7	80.9	94.0	77.1	110.2	78	70.0
419	709.0	635.7	868.9	783.9	687.4	823	808.7
1168	995.8	1051.5	1091.9	1033.2	992.7	998	1004.4
5.5	8.1	7.5	10.7	10.0	9.0	9.7	9.2
60	124.9	89.0	146.2	132.8	115.4	144	138.7
	29.0	21.2	39.5	30.6	33.0	43.1	38.1
6.6	14.9	12.7	18.0	16.7	14.7	19.3	18.0
3.2	19.2	18.5	29.2	26.3	23.2	27.6	24.5
17.7	12	12.5	13.1	12.9	12.6	13.8	9.5
320	109	67.8	167.4	130.7	106.8	148	139.4
11.9	7.9	8.5	8.1	7.3	8.2	7.7	7.4
53	39	39.4	38.5	35.9	35.5	34.4	35.1
106	79.6	79.8	76.3	75.7	76.3	70.4	74.3
41	34.6	32.2	35.7	33.1	32.0	32.3	33.2
6.7	6.0	5.7	6.3	6.1	5.6	5.8	5.7
1.29	1.5	1.2	1.6	1.5	1.3	1.27	1.3
4.4	4	3.8	4.4	4.3	3.9	4.5	4.4
3.2	2.4	2.3	2.6	2.3	2.4	2.5	2.2
1.5	1	1.2	1.1	1.0	1.1	0.6	1.1
1.57	1	1.0	1.0	1.0	0.9	0.98	0.9
20.4	11.8	14.3	6.7	8.9	11.0	7.2	7.2
	0.706803	0.707020	0.7065126			0.706695	0.706724

0.000005	0.000006	0.000007
0.512367	0.512343	0.5124024
0.000004	0.000005	0.000006
18.216489	18.211948	18.364697
	0.0008	0.0007
15.615155	15.617531	15.622513
	0.0008	0.0006
38.580263	38.577030	38.636606
	0.0022	0.0019

0.000004	0.000006
0.512371	0.512365
0.000003	0.000002
18.273684	18.269987
15.618642	15.615501
38.606640	38.597552

Table 2

« Stage »	Ampato Basal edifice	Ampato Upper edifice	Sabancaya
Rock type		Lava flow	
Compositional range	Andesite (57.2 – 62.9 wt.% SiO <sub>2</sub> )	Andesite (57.6 – 62.1 wt.% SiO <sub>2</sub> )	Andesite (60.9 – 62.8 wt.% SiO <sub>2</sub> )
Mineral assemblage	Pl+Cpx±Opx±Amp±Bt±Ol+Mag	Pl+Cpx±Opx±Amp±Bt+Mag	Pl+Cpx±Opx+Amp+Bt+Mag
Phenocrysts % vol.	20–60%	30–60%	30–55%
Texture	porphyritic and microlitic, sometimes with intersertal groundmass	porphyritic, sometimes with intersertal groundmass	porphyritic, sometimes with intersertal groundmass
Vesicularity (%)	4–8	4–8	4–8
Other characteristics	Some plagioclase phenocrysts with sieve-cored and/or sieve-ringed.	Some plagioclase phenocrysts with sieved cores and/or rings. Amphibole phenocryst sometimes have thin reaction rims composed of oxides. Some biotite phenocrysts have thin reaction rims composed of plagioclase and oxides.	Some plagioclase phenocrysts with sieved cores and/or rings. Amphibole phenocryst sometimes have altered rims or black-type of alteration (completely replaced by an aggregate of Fe-Ti oxides and pyroxene).
Compositional range	Dacite (63.6 – 65.1 wt.% SiO <sub>2</sub> )	Dacite (63.1 – 67.3 wt.% SiO <sub>2</sub> )	Dacite (63.2 – 65.7 wt.% SiO <sub>2</sub> )
Mineral assemblage	Pl+Cpx±Opx+Amp+Bt+Mag	Pl+Cpx±Opx+Amp+Bt+Mag	Pl+Cpx±Opx+Amp+Bt+Mag
Phenocrysts % vol.	10–50%	10–50%	30–50%
Texture	porphyritic, sometimes with intersertal groundmass	porphyritic, sometimes with intersertal groundmass	porphyritic, sometimes with intersertal groundmass
Vesicularity (%)	2–6	0–4	4–8
Other characteristics	Some plagioclase phenocrysts are sieve-cored and/or sieve-ringed. Amphibole and biotite phenocrysts sometimes have altered rims or black-type of alteration (completely replaced by an aggregate of Fe-Ti oxides and pyroxene).	Some plagioclase phenocrysts are sieve-cored and/or sieve-ringed. Amphibole phenocryst sometimes have altered rims or black-type of alteration. Some biotite phenocrysts have thin reaction rims composed of plagioclase and Fe-Ti oxides.	Some plagioclase phenocrysts are sieve-cored and/or sieve-ringed. Amphibole phenocryst sometimes have altered rims or black-type of alteration (completely replaced by an aggregate of Fe-Ti oxides and pyroxene).
Rock type	Pumice or scoria belonging to pyroclastic-flow and tephra-fall deposits, or ballistic bombs		
Compositional range	---	Andesite (57.6 – 59.2 wt.% SiO <sub>2</sub> )	Andesite (61.1 – 61.2 wt.% SiO <sub>2</sub> )
Mineral assemblage		Pl+Cpx±Opx±Amp+Mag	Pl+Cpx+Opx+Amp+Bt+Mag
Phenocrysts % vol.		10–30%	40–50%
Texture		Vitroclastic	porphyritic with intersertal groundmass
Vesicularity (%)		40–60	4–10
Other characteristics		Some plagioclase phenocrysts are sieve-cored and/or sieve-ringed. Amphibole phenocryst sometimes have thin reaction rims composed of oxides.	Some plagioclase phenocrysts are sieve-cored and/or sieve-ringed. Biotite phenocryst have thin reaction rims composed of plagioclase and oxides.
Compositional range	Rhyolite (74.2 – 75.7 wt.% SiO <sub>2</sub> ), G4	Dacite (65.0 – 69.2 wt.% SiO <sub>2</sub> ), G2, G3	---
Mineral assemblage	Pl+Bt+Mag±Qz	Pl+Cpx±Opx+Amp+Bt+Mag	
Phenocrysts % vol.	10–20%	10–20%	
Texture	Vitroclastic	porphyritic, sometimes with intersertal groundmass; vitroclastic	
Vesicularity (%)	30–40	50–60	
Other characteristics	Biotite phenocryst sometimes has altered rims or black-type of alteration (completely replaced by an aggregate of Fe-Ti oxides and pyroxene).	Some plagioclase phenocrysts are sieve-cored and/or sieve-ringed. Amphibole phenocryst sometimes have altered rims.	

Table 3

« Stage »	Ampato Basal edifice	Ampato Upper edifice	Sabancaya
Compositional range <sup>a</sup>	Andesite to rhyolite (57.2 – 75.7 wt.% SiO <sub>2</sub> )	Andesite to dacite (57.6 – 67.3 wt.% SiO <sub>2</sub> )	Andesite to dacite (60.9 – 65.7 wt.% SiO <sub>2</sub> )
Plagioclase % An pheno <sup>b</sup>	24 – 72	28 – 75	27 – 63
Type of zoning <sup>b</sup>	Normal (e.g., andesite SA-1162: An <sub>70-63</sub> ; rhyolite 1142D: An <sub>33-22</sub> ) and reverse zoning (e.g., andesite SA-1102: An <sub>48-54</sub> )	Normal (e.g., andesite SA-1165: An <sub>31-26</sub> ; dacite SA-1014A: An <sub>35-31</sub> ) and reverse zoning (e.g., andesites SA-1165: An <sub>34-48</sub> ; dacite SA-1014B: An <sub>29-46</sub> )	Normal (e.g., andesite SA-0904: An <sub>34-29</sub> ; dacite SA-1015: An <sub>34-32</sub> ) and reverse zoning (e.g., andesite SA-0911: An <sub>33-60</sub> ; dacites SA-0919: An <sub>32-52</sub> )
Clinopyroxene compositional range <sup>b</sup>	En <sub>39-52</sub> -Fs <sub>12-19</sub> -Wo <sub>34-46</sub>	En <sub>39-46</sub> -Fs <sub>13-19</sub> -Wo <sub>40-46</sub>	En <sub>39-48</sub> -Fs <sub>11-17</sub> -Wo <sub>41-48</sub>
Orthopyroxene % En <sup>b</sup>	65 – 76	62 – 75	41 – 76
Amphibole Mg# <sup>c</sup>	74 – 78	72 – 83	70 – 89
Biotite <sup>b</sup>	1.14 < Al <sup>T</sup> < 2.09	1.12 < Al <sup>T</sup> < 1.17	1.12 < Al <sup>T</sup> < 1.18
Olivine % Fo <sup>b</sup>	68 – 77		80 – 82
Fe-Ti oxides <sup>b</sup>	Ulvospinel-magnetite and ilmenite series	Ulvospinel-magnetite and ilmenite series	Ulvospinel-magnetite and ilmenite series

<sup>a</sup>XRF analyses of bulk juvenile clasts on an anhydrous basis; *n* n°. of samples

<sup>b</sup>Range of microprobe analyses of phenocrysts

<sup>c</sup>Range of microprobe analyses; Mg# [where Mg# = 100\*Mg/(Mg + Fe<sup>T</sup>) in mol.%, and Fe<sup>T</sup> is total iron as Fe<sup>2+</sup>]

# SEM 1

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76	751	760
77	761	770
78	771	780
79	781	790
80	791	800

Page	Start	End
81	801	810
82	811	820
83	821	830
84	831	840
85	841	850
86	851	860
87	861	870
88	871	880
89	881	890
90	891	900

Page	Start	End
91	901	910
92	911	920
93	921	930
94	931	940
95	941	950
96	951	960
97	961	970
98	971	980
99	981	990
100	991	1000

Page	Start	End
101	1001	1010
102	1011	1020
103	1021	1030
104	1031	1040
105	1041	1050
106	1051	1060
107	1061	1070
108	1071	1080
109	1081	1090
110	1091	1100

Page	Start	End
111	1101	1110
112	1111	1120
113	1121	1130
114	1131	1140
115	1141	1150
116	1151	1160
117	1161	1170
118	1171	1180
119	1181	1190
120	1191	1200

Page	Start	End
121	1201	1210
122	1211	1220
123	1221	1230
124	1231	1240
125	1241	1250
126	1251	1260
127	1261	1270
128	1271	1280
129	1281	1290
130	1291	1300

Page	Start	End
131	1301	1310
132	1311	1320
133	1321	1330
134	1331	1340
135	1341	1350
136	1351	1360
137	1361	1370
138	1371	1380
139	1381	1390
140	1391	1400

Page	Start	End
141	1401	1410
142	1411	1420
143	1421	1430
144	1431	1440
145	1441	1450
146	1451	1460
147	1461	1470
148	1471	1480
149	1481	1490
150	1491	1500

Page	Start	End
151	1501	1510
152	1511	1520
153	1521	1530
154	1531	1540
155	1541	1550
156	1551	1560
157	1561	1570
158	1571	1580
159	1581	1590
160	1591	1600



## SEM 2

Edifice	Ampato Basal															
Volcanic stage	Former andesitic cone												Moidepampa			
Sample	SA-1161	SA-1162	SA-1164	SA-1102	SA-1103	SA-1124	SA-1117	SA-1122	SA-1166	SA-1010	SA-1108	SA-1109	SA-1032	SA-1101	SA-1105	
Location	W flank, Ampato	W flank, Ampato	W flank, Ampato	SE flank, Ampato	SE flank, Ampato	South flank, Ampato	South flank, Ampato	South flank, Ampato	W flank, Ampato	E flank, Ampato	South flank, Ampato	South flank, Ampato	SE flank, Ampato	SE flank, Ampato	South flank, Ampato	
UTM-North	8,249,025	8,249,025	8,249,025	8,244,360	8,244,656	8,240,139	8,242,674	8,240,517	8,248,393	8,248,399	8,240,399	8,240,220	8,239,778	8,244,253	8,243,190	
UTM-East	189,617	189,617	189,617	195,403	195,706	189,809	192,847	189,949	188,439	201,368	194,111	193,453	195,234	195,369	194,897	
Rock type	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	
Major oxide (wt.%)																
SiO <sub>2</sub>	56.43	56.19	60.28	57.3	58.0	57.3	59.5	57.8	58.52	60.53	56.61	57.51	57.15	64.1	63.4	
TiO <sub>2</sub>	1.10	1.12	0.86	1.21	1.17	1.05	1.07	1.16	1.04	0.83	1.09	1.10	1.24	0.79	0.82	
Al <sub>2</sub> O <sub>3</sub>	16.92	17.25	15.76	16.7	16.6	17.8	17.1	17.5	17.30	16.51	17.69	18.17	17.86	15.8	15.7	
Fe <sub>2</sub> O <sub>3</sub>	7.34	7.24	5.46	7.26	7.13	6.70	6.30	7.31	6.56	5.27	7.12	6.82	6.22	4.57	4.77	
MnO	0.10	0.10	0.07	0.08	0.08	0.09	0.07	0.09	0.08	0.08	0.09	0.09	0.07	0.06	0.06	
MgO	3.28	3.14	2.20	3.48	3.58	3.03	2.48	3.31	2.51	2.11	3.21	2.85	2.61	1.90	2.00	
CaO	6.54	6.15	4.57	5.99	5.97	6.13	5.35	6.15	5.32	4.4	6.6	6.0	5.4	3.91	3.97	
Na <sub>2</sub> O	4.04	4.22	3.61	4.52	4.48	4.19	4.48	4.39	4.57	4.0	4.3	4.5	4.4	4.39	4.28	
K <sub>2</sub> O	2.30	2.46	3.74	2.50	2.60	2.32	2.76	2.18	2.56	3.7	2.0	2.1	2.4	3.46	3.33	
P <sub>2</sub> O <sub>5</sub>	0.36	0.42	0.28	0.45	0.44	0.34	0.38	0.38	0.38	0.3	0.3	0.4	0.4	0.30	0.31	
LOI	0.5	1.0	1.8	0.21	-0.03	0.79	0.09	0.06	0.05	1.0	0.3	0.4	1.5	0.44	0.77	
TOTAL	98.94	99.30	98.65	99.78	100.02	99.72	99.52	100.25	98.90	98.7	99.3	99.9	99.3	99.76	99.46	
Trace elements (ppm)																
Rb	49.8	59.2	104.8	60	61	50	77	47	59.3	80.3	42.6	35.7	54.9	113	116	
Sr	849.7	988.9	679.2	977	917	851	904	840	902.7	744.5	810.0	841.4	927.2	750	747	
Ba	920.1	1147.7	1014.5	1138	1122	1019	1164	1041	1139.2	1589.0	835.8	957.8	1046.1	1084	1129	
Sc	11.8	12.8	9.8	13.2	13.3	12.5	11.1	13.3	10.5	9.9	15.0	12.0	11.9	7.7	8.0	
V	179.4	174.9	124.2	170	169	157	153	178	149.5	106.2	182.6	159.7	175.7	100	105	
Cr	50.8	18.8	19.0	93.7	97.7	30.0	22.5	45.8	14.9	12.7	43.2	33.6	73.7	23.7	25.0	
Co	23.6	23.6	15.0	22.5	21.7	20.3	16.9	22.2	18.0	13.5	21.9	19.8	18.6	12.4	13.1	
Ni	33.3	22.5	18.0	49.1	50.8	26.8	23.1	34.3	19.3	16.3	33.9	29.1	36.6	16.8	23.6	
Y	14.0	16.3	16.5	14.5	14.6	15.4	14.4	17.4	14.8	19.5	16.5	17.6	18.4	11.7	11.8	
Zr	180.8	216.6	213.5	222	233	204	226	197	223.5	309.7	177.9	198.1	214.7	142	155	
Nb	6.7	8.1	9.6	8.8	8.9	6.9	8.5	7.0	8.5	12.6	6.2	7.1	12.5	8.7	8.9	
La	30.90	41.1	40.9	45	44	37	42	38	40.5	63.9	35.9	39.4	19.9	43	43	
Ce	64.74	86.0	84.8	90	90	74	85	73	85.6	119.3	68.6	85.7	39.0	87	87	
Nd	32.18	39.1	35.6	41	42	35	39	38	36.8	45.9	36.7	46.5	13.6	35	36	
Sm	5.82	6.8	6.5	7.3	7.6	6.2	6.5	6.6	6.7	9.0	6.1	6.7	9.0	6.0	6.3	
Eu	1.53	1.8	1.4	1.79	1.78	1.69	1.52	1.79	1.7	1.8	1.7	1.7	2.4	1.29	1.36	
Gd	4.16	4.8	4.4	5.0	4.7	4.6	4.6	4.9	4.5	5.4	4.9	5.3	6.2	3.8	4.2	
Dy	2.85	3.2	3.0	2.8	2.9	2.9	2.8	3.2	2.9	3.5	3.1	3.2	3.6	2.3	2.3	
Er	1.35	1.5	1.7	1.1	1.2	1.1	1.1	1.4	1.3	1.6	1.4	1.5	1.5	0.5	0.9	
Yb	1.19	1.4	1.4	1.06	1.10	1.21	1.13	1.27	1.1	1.6	1.3	1.3	1.3	0.93	0.94	





Ampato Upper															
Riolitic sequence												Yanajaja			
SA-1114	SA-1115	SA-1137	SA-1138	SA-1106	SA-0927	SA-1130	SA-1142A	SA-1142D	SA-1184C	SA-1186A	SA-1186B	SA-1184A	SA-1184D	SA-1023	SA-1128
W flank Ampato	South flank Ampato	SW flank, base Ampato	SW flank Ampato	South flank Ampato	W flank, Ampato	SW flank	Road to Cabanaconde	Road to Cabanaconde	Road Pedregal-Querque	Road Huambo-Querque	Road Huambo-Querque	Road Pedregal - Querque	Road Pedregal - Querque	East flank Ampato	S flank Ampato "Yanajaja"
8,241,698	8,243,491	8,246,350	8,247,137	8,243,432	8,247,869	8,245,701	8,244,160	8,244,160	8,234,467	8,248,692	8,248,692	8,234,467	8,234,467	8,249,155	8,244,402
184,106	192,405	187,567	188,471	194,252	184,099	188,519	182,345	182,345	809,521	808,904	808,904	809,521	809,521	194,225	189,043
Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Fallout tephra	Fallout tephra	Fallout tephra	Fallout tephra	Fallout tephra	Fallout tephra	Fallout tephra	Lava flow	Lava flow
62.1	64.2	61.9	62.8	63.3	61.94	63.0	70.74	71.12	74.7	72.3	71.6	70.62	71.71	61.51	61.1
0.97	0.80	0.85	0.88	0.77	0.91	0.91	0.14	0.16	0.12	0.24	0.23	0.16	0.11	1.01	0.93
16.0	15.5	16.0	15.5	15.8	16.03	15.9	13.58	12.65	12.3	13.6	13.4	12.47	11.97	16.32	16.1
5.22	4.54	4.83	4.95	4.52	5.01	5.07	0.80	1.30	0.71	1.32	1.26	0.98	0.62	5.55	5.42
0.06	0.05	0.06	0.06	0.06	0.06	0.06	0.04	0.04	0.043	0.051	0.051	0.08	0.04	0.07	0.07
2.28	1.83	2.00	1.99	1.90	2.18	1.98	0.14	0.22	0.13	0.31	0.27	0.21	0.12	2.47	2.66
4.10	3.72	3.84	3.91	3.84	4.41	4.06	0.59	0.69	0.79	1.39	1.28	0.89	0.74	5.01	4.81
4.27	4.12	4.01	4.19	4.10	4.47	3.29	2.62	3.17	2.09	3.41	3.47	2.84	2.16	4.39	4.18
3.32	3.57	3.45	3.44	3.41	3.19	3.47	4.76	4.36	6.24	4.75	4.53	5.18	5.75	2.85	2.93
0.36	0.28	0.30	0.32	0.29	0.33	0.36	0.01	0.02	0.006	0.037	0.028	0.03	0.00	0.34	0.32
0.86	0.64	0.74	0.26	1.01	0.36	0.03	5.3	4.2	4.74	5.26	5.30	4.71	4.81	0.17	1.22
99.58	99.30	98.02	98.28	99.01	98.89	98.16	98.75	97.92	101.79	102.72	101.45	98.16	98.02	99.69	99.71
113	140	117	134	123	105.7	121	234.5	231.4	214	156	160	134.8	219.8	97.4	87
780	693	734	704	755	840.7	820	86.9	106.1	92	263	237	140.9	74.6	834.8	771
1048	1020	1065	983	1073	1155.1	1112	791.6	1086.2	747	1190	1167	1173.8	530.8	1047.0	977
8.7	7.5	7.8	7.5	7.8	8.6	7.7	3.0	3.0	2.6	2.6	2.4	2.6	2.5	9.09	10.6
117	98	103	109	100	111.7	111	5.0	8.9	4.8	12	10	5.6	4.7	127.45	125
42.6	34.3	39.7	39.8	22.7	27.7	42.8			0.9	1.3	1.7	1.7	1.5	38.94	46.1
15.2	11.8	13.1	14.1	12.4	15.0	13.4	0.8	1.7	0.0	0.4	3.9	0.3	0.3	16.35	16.0
22.9	20.6	22.8	21.8	31.3	22.4	22.0	1.4	3.7	0.0	0.0	0.0	1.2	0.9	26.49	30.9
14.0	13.1	13.2	13.1	11.7	12.4	12.9	8.8	10.0	8.0	8.0	7.8	12.0	7.4	12.24	12.8
155	146	152	143	147	146.1	186	79.3	84.7	70	174	170	90.9	66.5	136.09	133
9.5	9.3	9.4	9.3	8.7	9.5	10.0	12.0	12.0	9.9	9.9	9.4	12.8	10.9	12.75	7.8
51	45	46	44	43	45.2	49	19.9	24.2	29	29	29	20.0	25.0	36.48	38
101	92	95	89	86	89.8	99	39.0	52.2	54	67	63	56.4	46.2	76.33	79
45	38	40	39	35	38.5	42	13.6	17.7	18	20	20	15.2	14.7	34.62	35
7.5	6.1	6.6	6.7	6.0	6.2	6.9	2.4	3.3	3.0	3.1	2.9	3.1	2.4	5.99	6.1
1.63	1.32	1.38	1.38	1.32	1.5	1.54	0.4	0.6	0.53	0.81	0.73	0.6	0.4	1.46	1.53
5.0	4.2	4.3	4.5	4.3	4.3	4.4	2.0	2.4	2.0	2.1	1.9	2.3	1.4	4.17	4.2
2.9	2.5	2.7	2.6	2.3	2.5	2.6	1.4	1.6	1.2	1.3	1.2	1.8	1.1	2.28	2.6
1.0	0.7	1.0	1.2	0.9	1.0	1.0	0.7	0.6	0.4	0.2	0.5	0.8	0.5	1.05	1.0
1.05	1.04	1.06	1.02	0.90	0.9	0.97	0.9	0.9	0.72	0.75	0.73	1.2	0.7	0.90	1.00

13.0	16.4	15.7	14.5	13.5	10.0	12.7	25.9	21.3	22.8	15.1	15.3	8.8	23.8	8.54	9.7
		0.706630	0.706582					0.707254	0.707421	0.707176		0.708776	0.707407		0.706548
		0.000016	0.000007					0.000007	0.000007	0.000007		0.000007	0.000009		0.000006
		0.512382	0.512386									0.512108	0.512296		0.512394
		0.000004	0.000004									0.000007	0.000003		0.000005
		18.229431	18.254171					18.214337	18.209962	18.168753		17.8166975	18.2039835		18.244236
		0.0007	0.0008					0.0003	0.0003	0.0004		0.0006	0.0007		0.0005
		15.615043	15.617141					15.613802	15.612198	15.609403		15.5991906	15.6127407		15.6150
		0.0007	0.0007					0.0004	0.0003	0.0004		0.0006	0.0008		0.0005
		38.553807	38.584347					38.506368	38.487431	38.468839		38.7149734	38.4968113		38.5685
		0.0018	0.002					0.0011	0.0009	0.0013		0.0018	0.002		0.001

North Cone					South Cone										
SA-0931	SA-1175A	SA-1175B	SA-1176	SA-1177	SA-1016A	SA-1016C	SA-1014A	SA-1014B	SA-0928	SA-1173	SA-0930	SA-1026A	SA-1026B	SA-1165	SA-1160
SE flank Ampato	N Flank Ampato	N Flank Ampato	N Flank Ampato	N Flank Ampato	SE flank Sabancaya	SE flank Sabancaya	SE flank Sabancaya	SE flank Sabancaya	SE flank Ampato	East flank Ampato	SE flank Ampato	East flank Ampato	East flank Ampato	W flank, Ampato	East flank Ampato
8,245,728	8,251,299	8,251,299	8,251,058	8,250,965	8,248,912	8,248,912	8,248,736	8,248,736	8,247,356	8,248,582	8,247,108	8,246,215	8,246,215	8,250,264	8,247,759
192,947	193,121	193,121	193,196	193,431	195,902	195,902	195,842	195,842	193,526	192,940	193,200	195,224	195,224	187,602	188,305
Lava flow	Lava flow	Lava flow	Lava flow	enclave co-magmatic	Scoria flow	Scoria flow	Juvenile block	Juvenile block	Lava flow	Lava flow	Lava flow	Juvenile block	Juvenile block	Lava flow	Lava flow
62.00	60.27	57.04	61.48	57.05	59.6	65.4	64.3	62.3	62.22	62.78	61.79	64.58	62.25	61.60	63.33
0.83	0.97	1.23	0.96	1.19	1.07	0.63	0.64	0.83	0.87	0.81	0.83	0.62	0.82	0.96	0.9
15.54	16.24	16.84	16.25	16.83	16.3	15.0	15.0	15.6	15.88	15.61	15.56	14.96	15.54	16.26	15.57
5.03	5.61	7.25	5.54	7.27	6.03	3.84	3.98	4.70	5.12	4.85	4.98	3.77	4.77	5.80	5.057
0.07	0.07	0.08	0.07	0.09	0.07	0.05	0.05	0.06	0.07	0.06	0.07	0.05	0.06	0.07	0.06
2.23	2.60	3.23	2.33	3.31	2.49	1.52	1.53	1.89	2.43	2.05	2.21	1.50	1.88	2.78	1.97
4.43	5.08	6.38	4.83	6.25	4.92	3.39	3.35	4.18	4.60	4.23	4.41	3.35	3.98	5.06	4.18
4.09	4.26	4.11	4.32	4.08	3.27	3.96	4.01	4.28	4.24	4.25	4.07	4.03	4.19	4.27	4.20
3.10	2.84	2.44	2.93	2.52	2.76	3.51	3.53	3.23	3.03	3.30	3.11	3.53	3.26	2.87	3.460
0.28	0.33	0.45	0.35	0.41	0.39	0.13	0.21	0.30	0.27	0.32	0.26	0.20	0.29	0.30	0.33
1.45	0.3	0.5	0.25	0.67	0.50	2.41	1.70	1.44	0.13	0.02	1.23	1.64	1.50	0.11	0.2
99.04	98.57	99.57	99.30	99.67	97.40	99.80	98.29	98.84	98.86	98.27	98.50	98.23	98.55	100.08	99.23
87.5	88.9	66.1	83.1	57.8	94.4	99.0	92.4	92.0	80.6	112.24	77.1	133.5	113.3	84.07	134.57
686.6	821.4	1001.2	833.6	930.1	905.1	599.1	593.7	755.0	714.8	755.71	678.1	598.0	722.3	762.27	727.46
1001.1	1036.3	1009.9	1083.6	980.0	1008.9	920.8	973.5	1112.6	972.4	1092.81	1004.9	974.4	1094.2	956.90	1013.10
9.3	10.1	12.1	8.8	12.4	9.1	7.1	6.8	7.6	9.79	8.57	9.25	6.32	7.64	10.88	7.58
113.5	128.6	177.4	118.4	159.6	139.4	81.9	84.0	103.1	117.95	105.43	113.22	79.24	103.75	137.75	111.29
32.3	49.3	50.6	32.5	44.1	41.9	22.4	23.4	22.3	38.69	37.43	34.19	23.26	27.51	44.92	42.08
14.6	16.1	20.9	16.4	19.8	17.6	10.4	10.4	13.8	15.29	13.42	14.48	10.79	13.15	17.69	13.90
23.4	23.4	28.3	23.3	28.4	28.0	14.2	15.2	16.9	28.31	21.57	24.08	13.19	17.60	31.31	24.53
13.1	12.6	13.5	12.2	14.0	11.9	11.1	12.1	11.9	12.63	11.81	12.49	11.64	11.74	14.02	14
132.0	129.0	185.2	140.1	163.4	191.8	67.8	78.6	142.2	128.48	145.34	134.01	74.91	131.48	139.42	142
7.8	8.2	8.3	9.6	7.1	9.0	8.6	8.0	8.6	7.75	9.23	8.01	11.27	11.15	7.69	9
38.4	38.1	37.0	39.4	35.0	40.0	34.5	41.2	41.8	36.13	44.16	37.03	38.14	41.13	37.25	45.1
77.8	80.1	80.4	82.4	76.5	80.7	66.4	82.6	83.9	72.57	90.06	73.97	78.06	84.89	76.23	91
32.9	34.9	38.5	35.5	35.7	36.9	26.7	32.3	35.4	31.80	36.76	31.97	30.35	34.67	34.06	39.2
5.9	6.5	7.1	6.3	6.7	6.6	4.6	5.8	6.1	5.60	6.08	5.38	5.49	6.07	6.19	6.7
1.3	1.5	1.7	1.6	1.6	1.6	1.0	1.2	1.5	1.27	1.44	1.25	1.22	1.43	1.57	1.5
3.9	4.0	4.9	4.1	4.6	4.2	3.0	3.5	3.9	3.86	3.97	3.74	3.49	3.95	4.25	4.4
2.5	2.5	2.7	2.3	2.7	2.3	2.0	2.2	2.2	2.37	2.23	2.26	2.07	2.27	2.58	3
1.2	1.2	1.2	0.9	1.1	0.9	0.7	1.0	1.1	1.15	0.73	1.00	0.95	0.97	1.04	1.2
1.0	1.0	1.0	0.9	1.0	0.8	0.9	1.0	0.9	0.95	0.89	1.01	0.93	0.92	1.09	1

11.3	8.5	4.3	8.9	5.0	6.0	15.1	15.2	10.6	10.66	10.91	11.04	15.01	11.27	9.84	16
0.7065485		0.707523	0.706656	0.706532	0.706418	0.706989				0.706477	0.706617			0.706477	
0.000006		0.000006	0.000006	0.000007	0.000005	0.000006				0.000007	0.000006			0.000007	
0.512394		0.512299	0.512383	0.512400	0.512409	0.512343				0.512391	0.512388			0.512391	
0.000005		0.000004	0.000004	0.000004	0.000007	0.000005				0.000005	0.000004			0.000005	
18.252469			18.2818010	18.32634	18.4239471	18.2097697					18.288371			18.2589901	
			0.0007	0.0006	0.0006	0.0008					0.0009			0.0004	
15.617225			15.6186655	15.618492	15.6241859	15.6135833					15.616835			15.6159368	
			0.0006	0.0006	0.0006	0.0007					0.0008			0.0005	
38.581405			38.6106823	38.624074	38.6407370	38.5463641					38.588260			38.5762494	
			0.0018	0.0015	0.0015	0.002					0.002			0.001	

								Scoriaceous tephra							Corinta fallout
SA-1144	SA-1024A	SA-1024B	SA-1156B	SA-1021	SA-1025	SA-1020A	SA-1020B	SA-1033C	SA-1033D	SA-1133B	SA-1134	SA-1131	SA-1033E	SA-1119	SA-1127A
South flank Ampato	East flank Ampato	East flank Ampato	W flank Ampato	East flank Ampato	East flank Ampato	East flank Ampato	East flank Ampato	Road Sallalli-Taya	Road Sallalli-Taya	Road Sallalli-Taya	Road Sallalli-Taya	W flank Ampato	S flank Ampato	South flank Ampato	Collpa, SW flank Ampato
8,239,566	8,247,589	8,247,589	8,248,533	8,248,490	8,246,378	8,248,490	8,248,490	8,237,095	8,237,180	8,233,726	8,232,315	8,241,471	8,237,181	8,239,566	8,242,318
195,040	194,478	194,478	187,545	194,022	195,049	194,022	194,022	190,769	190,761	185,941	185,904	186,112	190,762	195,040	183,658
Pumice	Lava flow	Lava flow	Juvenile block	Lava flow	Lava flow	Lava flow	Lava flow	Bomb juvenile	Fallout tephra	Fallout tephra	Scoria	Scoria flow	Scoria	Scoria flow	Fallout tephra
64.62	62.13	64.48	62.77	61.62	62.06	62.55	65.56	56.71	56.30	56.5	57.7	57.6	53.4	57.7	63.2
0.62	0.90	0.65	0.88	0.90	0.90	0.87	0.63	1.2	1.2	1.10	1.10	0.98	1.22	1.02	0.69
15.25	15.30	14.70	15.86	16.03	15.99	15.85	14.74	17.59	17.29	17.617	16.384	17.3	17.1	17.9	15.9
3.44	5.04	3.93	4.70	5.20	5.12	4.97	3.78	7.445	6.741	6.84	6.62	6.92	7.43	6.80	3.83
0.04	0.06	0.05	0.06	0.07	0.06	0.06	0.05	0.10	0.08	0.09	0.08	0.09	0.10	0.09	0.05
0.87	2.09	1.54	2.05	2.38	2.11	2.05	1.50	2.83	2.34	2.90	2.92	3.06	3.21	2.37	1.01
2.33	4.24	3.28	4.35	4.69	4.40	4.23	3.23	5.87	4.90	5.54	5.62	5.66	5.63	5.44	2.51
3.47	4.38	3.99	4.38	4.25	4.42	4.37	4.02	4.12	3.86	3.882	4.196	3.31	3.76	3.79	3.18
4.45	3.18	3.57	3.12	3.02	3.20	3.24	3.64	2.166	2.402	2.26	2.47	2.64	1.97	2.56	4.37
0.14	0.34	0.20	0.33	0.31	0.34	0.34	0.23	0.34	0.36	0.36	0.39	0.29	0.41	0.30	0.17
3.50	0.22	1.18	0.1	0.78	0.30	0.39	1.53	1.96	4.57	2.93	0.73	1.14	4.94	2.02	4.66
98.74	97.89	97.60	98.56	99.24	98.89	98.92	98.91	100.37	100.00	100.05	98.20	99.04	99.21	99.98	99.58
207	92.7	126.4	93.13	81.9	97.1	110.53	145.67	49.9	67.3	61.5	64.5	82	46	76	182
417	812.0	571.1	777.97	778.8	834.5	809.57	577.08	835.0	840.9	876.2	894.9	747	972	725	438
1100	1106.9	945.1	1060.94	1035.4	1130.0	1148.21	968.77	948.8	1165.7	1092.8	1069.7	958	1132	1026	1186
5.7	8.05	6.43	6.68	9.18	8.34	7.93	6.09	13.0	11.1	12.4	11.6	12.9	12.9	13.1	6.1
61	113.05	84.24	105.16	117.76	114.76	110.71	79.27	181.1	138.4	142.8	159.2	155	150	157	70
	30.11	24.86	27.65	33.42	30.34	29.39	24.20	7.5	24.8	57.5	61.0	33.0	87.7	33.0	1.3
6.5	14.39	10.66	13.44	15.39	13.97	13.50	14.96	21.2	25.3	25.4	31.9	20.3	24.8	18.6	9.3
4.6	22.67	15.04	20.57	24.20	20.60	20.55	15.23	16.4	25.4	35.8	38.2	25.8	51.3	15.2	5.1
17.6	11.52	10.93	12.2	12.46	12.43	11.70	11.33	16.8	14.9	15.6	14.4	16.1	16.6	17.4	18.2
324	144.14	66.61	114.8	117.24	147.50	143.3	67.9	207	238	229.7	222.2	217	203	221	342
12.8	12.18	7.90	8.0	9.05	10.79	9.1	8.1	7	8	8.27	7.67	7.7	8.3	8.1	12.6
44	41.99	33.38	35.33	37.85	45.37	42.8	40.4	33.8	42.7	41.96	42.18	37	44	38	49
96	86.74	73.67	73.04	75.11	93.27	86.10	78.58	72	89	85.94	82.21	74	87	78	109
35	36.03	26.63	31.21	33.40	38.62	36.16	31.80	35.8	39.0	38.94	39.17	34	45	36	41
6.3	5.96	4.67	5.26	5.68	6.43	6.24	5.43	6.7	6.8	6.94	6.81	5.7	7.9	6.6	7.1
1.2	1.54	1.09	1.34	1.35	1.58	1.39	1.25	1.6	1.8	1.64	1.68	1.50	1.86	1.57	1.22
4.4	4.12	3.05	3.89	3.89	4.12	4.00	3.66	5.0	4.6	5	5	4.6	5.6	4.9	4.9
3.1	2.24	2.00	2.47	2.20	2.38	2.36	2.25	3	3	3	3	3.2	3.4	3.4	3.3
1.3	1.06	0.95	0.92	1.02	0.98	0.98	0.75	1.5	1.3	1	1	1.3	1.5	1.6	1.5
1.55	0.87	0.88	1.03	0.92	0.94	0.90	0.98	1	1	1.2	1.2	1.34	1.16	1.47	1.55

19.8	9.31	14.43	11.29	10.29	10.03	12.23	17.40	5	5	5	4	7.6	2.7	8.0	21.8
		0.707419		0.706734				0.706990					0.706325	0.707235	0.707495
		0.000007		0.000006				0.000007					0.000006	0.000008	0.000006
		0.512291		0.512370				0.512312					0.512431	0.512292	0.512297
		0.000006		0.000006				0.000008					0.000006	0.000005	0.000004
				18.2579341				18.1959294					18.488539	18.1778390	18.206377
				0.0006				0.0005					0.0006	0.0006	0.0007
				15.61772504				15.6122403					15.625302	15.6120386	15.61673
				0.0004				0.0005					0.0006	0.0005	0.0007
				38.5653709				38.5849021					38.714928	38.5880291	38.637404
				0.002				0.001					0.0015	0.0015	0.002

											<b>Central Cone</b>				
SA-1127B	SA-1127C	SA-1127D	SA-1139C	SA-1139A	SA-1033B	SA-1033A	SA-1143	SA-1126	SA-1112A	SA-1112B	SA-0929	SA-1154	SA-1155	SA-1157	SA-1159
Collpa, SW flank Ampato	Collpa, SW flank Ampato	Collpa, SW flank Ampato	Collpa, SW Ampato	Collpa, SW flank Ampato	South flank Ampato	South flank Ampato	Road Sallalli- Taya	Qda. Chuyune	SW Ampato, Q. Vizcachane	SW Ampato, Q. Vizcachane	SE flank Ampato	East flank Ampato	East flank Ampato	East flank Ampato	East flank Ampato
8,242,318	8,242,318	8,242,318	8,245,165	8,245,165	8,237,068	8,237,067	8,245,596	8,243,053	8,243,120	8,243,120	8,249,119	8,249,484	8,249,870	8,249,948	8,250,248
183,658	183,658	183,658	184,842	184,842	190,779	190,778	185,315	183,819	184,012	184,012	194,027	193,676	193,443	193,215	192,988
Fallout tephra	Fallout tephra	Fallout tephra	Pumice	Fallout tephra	Fallout tephra	Fallout tephra	pumice	Bomb	Pumice	Scoria	Lava flow	Lava flow	Lava flow	Lava flow	Dome
64.2	62.8	61.4	62.92	61.8	64.1	63.0	63.93	65.2	65.8	64.5	61.65	60.79	64.52	62.8	62.5
0.63	0.67	0.66	0.65	0.71	0.67	0.63	0.65	0.60	0.60	0.64	0.93	0.9	0.7	0.88	0.86
15.1	15.3	15.4	16.19	16.6	15.1	15.3	15.54	14.9	15.0	15.3	16.01	16.96	14.93	15.856	15.597
3.45	3.62	3.61	3.56	4.02	3.61	3.44	3.45	3.29	3.24	3.54	5.38	5.217	4.228	4.70	5.02
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.08	0.07	0.07	0.06	0.06	0.07
0.91	0.99	1.28	0.91	1.07	0.92	0.93	0.94	0.88	0.82	0.94	2.36	2.49	1.90	2.05	2.25
2.40	2.56	2.62	2.34	2.40	2.43	2.35	2.48	2.41	2.30	2.47	4.74	5.14	3.57	4.35	4.36
3.20	3.29	3.31	3.31	3.24	3.21	3.16	3.55	3.53	3.64	3.53	4.34	4.51	4.06	4.379	4.131
4.33	4.40	4.51	4.06	4.07	4.64	4.33	4.45	4.52	4.75	4.33	3.00	2.738	3.555	3.12	3.17
0.17	0.17	0.18	0.16	0.19	0.17	0.16	0.18	0.16	0.16	0.16	0.31	0.33	0.27	0.33	0.30
4.27	4.68	5.47	4.00	4.39	4.47	4.63	3.70	2.78	2.88	2.81	0.42	0.4	0.5	0.06	1.03
98.68	98.49	98.46	98.15	98.52	99.29	98.06	98.93	98.36	99.26	98.25	99.20	99.56	98.29	98.56	99.25
181	183	182	174.3	173	194	183	201.2	196	204	188	84.1	83.6	142.3	90.8	110.7
425	449	478	437.7	481	429	427	447.0	419	410	447	791.6	892.8	616.8	778.0	709.0
1098	1089	1141	1163.1	1222	1109	1101	1152.8	1168	1137	1161	1104.9	1044.5	1059.5	1060.9	995.8
5.6	5.9	5.7	5.9	6.4	5.6	5.9	5.8	5.5	5.3	5.9	9.3	9.0	6.7	6.7	8.1
62	67	66	60.7	70	68	63	64.2	60	59	66	123.8	117.3	92.7	105.2	124.9
0.1	0.1			0.2	0.1	0.5				1.1	33.6	37.7	28.5	27.7	29.0
7.4	7.0	7.5	7.6	8.9	6.3	6.5	7.2	6.6	6.2	6.9	15.6	15.5	12.2	13.4	14.9
4.8	3.5	3.6	2.3	3.4	3.4	3.7	3.2	3.2	1.8	3.1	23.9	25.3	18.5	20.6	19.2
17.2	17.2	19.1	19.1	19.2	18.2	18.6	18.0	17.7	17.3	20.0	12.4	12	12	9.48	12
320	321	309	348.0	350	327	323	337.9	320	333	325	127.50	120	68	114.8	109
12.2	12.5	11.6	12.5	12.7	12.6	12.3	13.0	11.9	12.4	12.1	8.00	7	8	8.02	7.9
50	50	57	51.9	54	52	51	46.8	53	40	59	36.70	37.4	43.4	39.55	39
108	106	107	110.2	113	105	109	101.3	106	98	122	77.45	73	86	77.40	79.6
40	39	44	41.4	43	42	41	38.3	41	34	46	33.63	35.3	34.5	33.87	34.6
6.6	6.5	7.6	7.2	7.8	7.2	7.3	6.7	6.7	5.8	7.8	6.12	6.2	5.8	5.65	6.0
1.23	1.23	1.29	1.3	1.30	1.19	1.28	1.3	1.29	1.04	1.46	1.45	1.6	1.3	1.48	1.5
4.7	4.7	4.8	5.0	5.1	5.0	5.0	4.8	4.4	4.7	5.3	4.02	4.1	4.0	4	4
3.2	3.0	3.5	3.5	3.5	3.4	3.4	3.2	3.2	2.9	3.4	2.24	2	2	2	2.4
1.0	1.2	2.0	1.5	1.3	1.8	1.9	1.7	1.5	0.9	1.4	1.12	0.9	1.0	1	1
1.53	1.51	1.61	1.7	1.68	1.59	1.60	1.6	1.57	1.55	1.73	0.96	1	1	0.8	1



20.4	20.5	19.6	21.8	20.8	20.5	21.0	19.5	20.4	19.7	19.8	10.05	8	16	10	11.8
				0.707419					0.707523						0.706803
				0.000007					0.000006						0.000005
				0.512291					0.512299						0.512367
				0.000006					0.000004						0.000004
				18.2093179					18.20258272						18.2164890
				0.0007					0.0010						
				15.6186259					15.61818768						15.6151545
				0.0006					0.0009						
				38.6359098					38.64562665						38.5802631
				0.0017					0.0023						

## Sabancaya

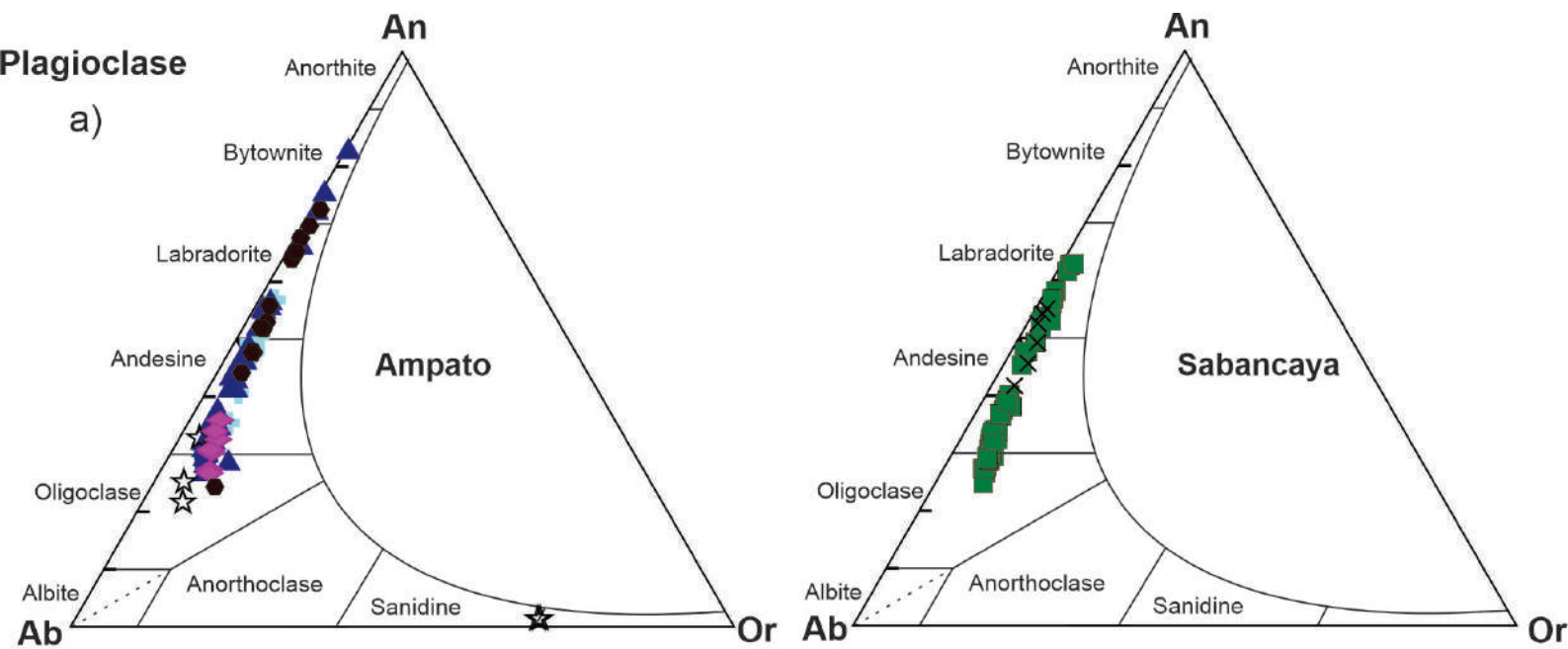
### Basal Sabancaya

SA-0906	SA-0915	SA-0918	SA-0926	SA-1147	SA-0924	SA-1150	SA-1152	SA-0911	SA-0912	SA-1149	SA-0917	SA-0921	SA-0922	SA-0934	SA-1148
East flank	East flank Sabancaya	East flank Sabancaya	W flank Sabancaya	NE of crater Sabancaya	W flank Sabancaya	NE flank Sabancaya	NE flank Sabancaya	East flank Sabancaya	SE flank Sabancaya	NE of crater Sabancaya	Flank NE Sabancaya volcano	W flank Sabancaya	W flank Sabancaya	NW flank Ampato	NE flank Sabancaya
8,248,272	8,253,513	8,250,933	8,251,693	8,252,138	8,251,829	8,253,585	8,253,165	8,254,122	8,250,147	8,255,222	8,255,870	8,252,921	8,251,850	8,252,006	8,253,552
197,456	199,052	198,619	187,176	2,000,121	190,508	198,579	199,534	198,900	194,428	196,406	196,910	192,220	191,886	191,086	197,841
Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow
61.0	64.9	62.1	61.8	63.66	60.1	63.9	61.4	61.6	61.55	62.8	60.7	60.1	60.8	59.65	61.8
0.95	0.73	0.93	0.90	0.8	0.99	0.78	0.97	0.96	0.9	0.86	1.01	1.01	0.96	1.07	0.96
16.2	15.5	16.2	16.2	14.47	16.6	15.69	15.59	16.4	15.83	16.167	16.1	16.6	16.2	16.55	16.475
5.63	4.17	5.34	5.22	4.54	5.73	4.09	5.29	5.52	5.588	4.82	6.10	5.93	5.61	6.23	5.62
0.08	0.06	0.07	0.07	0.06	0.07	0.06	0.07	0.07	0.07	0.06	0.08	0.07	0.07	0.08	0.07
2.92	1.96	2.40	2.31	1.91	2.54	2.33	2.48	2.52	2.91	2.34	3.03	2.91	2.77	2.81	2.60
5.32	3.77	4.76	4.67	3.73	5.29	3.92	4.64	5.22	5.04	4.53	5.38	5.52	5.16	5.45	5.14
4.17	4.12	4.36	4.35	4.07	4.41	4.13	4.30	4.25	4.08	4.23	4.18	4.28	4.18	4.43	4.291
2.80	3.50	3.03	3.05	3.312	2.71	3.49	2.98	2.79	2.875	3.11	2.63	2.56	2.78	2.68	2.84
0.29	0.23	0.33	0.30	0.30	0.34	0.27	0.37	0.30	0.27	0.29	0.30	0.30	0.29	0.38	0.34
0.24	0.52	0.29	0.30	0.7	0.19	0.49	0.15	0.13	0.2	0.34	0.19	0.07	0.16	0.24	-0.05
99.59	99.48	99.74	99.14	97.50	99.00	99.13	98.23	99.74	99.35	99.51	99.67	99.33	98.93	99.59	100.12
87.7	80.9	75.7	95.6	121.3	107.2	134.7	94.5	105.4	92.3	113.8	81.0	91.9	84.3	94.0	90.9
750.1	635.7	851.1	776.5	659.0	851.8	660.8	824.7	777.0	697.9	721.1	735.8	785.2	741.6	868.9	786.0
958.2	1051.5	1120.0	1030.7	976.3	1017.1	1172.4	1078.8	990.7	911.0	1052.7	886.4	920.6	959.3	1091.9	1018.0
11.2	7.5	9.2	8.6	7.1	9.5	7.9	8.8	9.5	10.7	8.4	10.5	10.1	10.0	10.7	9.3
134.1	89.0	122.3	121.2	101.0	134.1	85.2	120.4	126.9	129.8	106.8	145.7	138.0	127.1	146.2	130.0
48.3	21.2	32.3	32.2	30.5	35.3	22.9	37.5	39.5	50.6	27.6	71.5	62.6	53.4	39.5	40.3
17.6	12.7	15.7	14.9	13.5	16.9	13.8	16.2	16.2	17.6	14.3	19.3	18.5	17.1	18.0	16.7
30.2	18.5	24.3	23.7	20.4	26.6	20.5	25.7	25.2	31.5	21.5	41.8	36.5	32.9	29.2	25.1
13.7	12.5	12.6	12.3	9.9	12.5	12.5	10.9	12.8	12.9	12.0	13.0	12.4	12.9	13.1	12.3
99.9	67.8	134.2	119.2	11.4	145.1	12.8	12.1	119.0	98.1	12.4	116.2	117.2	109.5	167.4	12.5
7.9	8.5	8.2	8.7	8.3	7.8	8.2	7.7	7.3	7.3	7.6	7.3	7.2	7.7	8.1	7.4
35.3	39.4	41.8	37.5	42.4	37.1	40.6	42.7	34.6	35.1	37.1	32.1	32.2	33.3	38.5	36.6
71.9	79.8	84.6	75.0	81.2	76.1	82.5	89.8	72.6	70.4	74.4	70.5	66.8	72.0	76.3	74.3
32.4	32.2	36.2	32.5	35.0	34.2	34.9	38.2	32.3	31.6	32.4	31.5	31.1	31.5	35.7	34.1
5.8	5.7	6.5	5.8	6.3	6.1	6.0	6.7	6.0	5.4	5.6	5.7	5.7	5.6	6.3	5.8
1.4	1.2	1.5	1.4	1.4	1.6	1.3	1.7	1.5	1.4	1.4	1.4	1.5	1.4	1.6	1.5
4.0	3.8	4.1	3.9	4.1	4.1	4.2	4.4	3.9	4.2	3.9	4.1	3.7	4.1	4.4	4.2
2.5	2.3	2.4	2.3	2.4	2.4	2.4	2.7	2.4	2.6	2.4	2.4	2.3	2.4	2.6	2.6
1.1	1.2	1.1	0.9	0.9	1.2	0.9	1.1	1.0	0.8	0.9	1.1	1.0	1.1	1.1	0.9
1.0	1.0	1.0	0.9	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0	0.9	1.0	1.0	1.0

9.8	14.3	9.7	10.4	14.5	7.7	15.0	9.9	9.3	10.6	12.3	8.9	8.3	9.3	6.7	9.7
	0.707020									0.706888		0.706751		0.7065126	
	0.000006									0.000005		0.000006		0.000007	
	0.512343									0.512360		0.5123661		0.51240245	
	0.000005									0.000005		0.000010		0.000006	
	18.2119475									18.2245992		18.25375		18.3646968	
	0.0008											0.0005		0.0007	
	15.6175308									15.6141503		15.61592		15.6225128	
	0.0008											0.0005		0.0006	
	38.5770296									38.5800146		38.57911		38.6366061	
	0.0022											0.0020		0.0019	

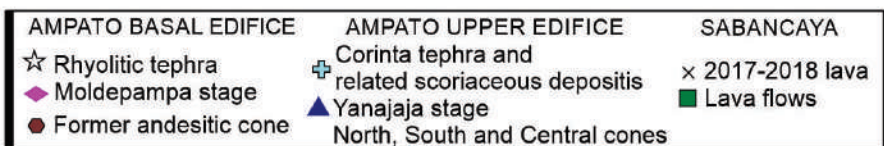
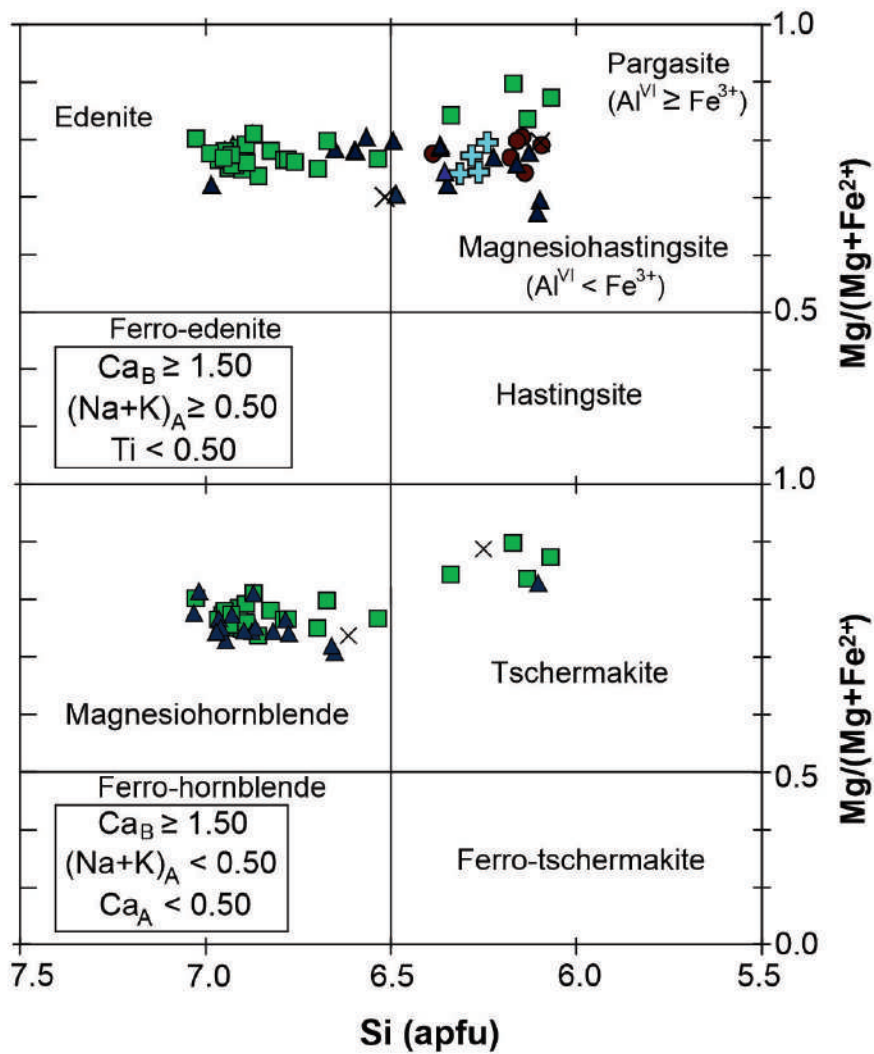
								Terminal Cone		2017-2018 Activity					
SA-0916	SA-0909	SA-1015	SA-1153	SA-0904	SA-0908	SA-0910	SA-0920	SA-0907	SA-0914	SA-0905	SA-0919	SA-1701	SA-1810	SA-1811	SA-1812
East flank Sabancaya	N flank Sabancaya	SE flank Sabancaya	NE of crater Sabancaya	South dome of Sabancaya	East flank Sabancaya	East flank Sabancaya	East flank Sabancaya	NE flank Sabancaya	East flank Sabancaya	East flank Sabancaya	W flank Sabancaya	SE flank Sabancaya	SE flank Sabancaya	SE flank Sabancaya	SE flank Sabancaya
8,250,440	8,255,474	8,248,962	8,255,567	8,251,215	8,248,067	8,247,323	8,250,471	8,252,810	8,251,054	8,252,631	8,252,245	8252130	8252344	8252221	8252374
196,444	193,838	195,836	196,923	193,257	198,395	199,617	198,738	194,470	194,713	194,966	192,587	194412	194350	194322	194290
Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Block juvenile	Block juvenile	Block juvenile	Block juvenile
62.1	62.0	63.6	62.9	61.9	61.7	60.7	60.7	61.1	64.7	61.8	62.5	60.2	60.82	61.18	60.95
0.90	0.90	0.78	0.91	0.90	0.91	1.00	0.95	0.95	0.73	0.94	0.87	1.00	0.92	0.95	0.94
16.1	16.2	15.2	16.114	16.0	15.9	16.6	16.5	16.3	15.6	16.3	15.8	16.2	16.58	16.44	16.40
5.39	5.25	4.74	5.16	5.41	5.32	5.77	5.67	5.63	4.01	5.42	5.15	6.2	5.73	5.89	5.88
0.07	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.076	0.08	0.08	0.08
2.41	2.33	2.12	2.11	2.44	2.39	2.91	2.85	2.51	2.05	2.50	2.26	2.74	2.50	2.66	2.56
4.86	4.77	4.06	4.53	4.82	4.70	5.48	5.28	5.04	3.85	5.01	4.54	5.46	5.58	5.48	5.55
4.21	4.22	4.25	4.25	4.28	4.31	4.27	4.29	4.20	4.09	4.26	4.14	4.34	4.40	4.35	4.36
2.94	2.99	3.35	3.17	3.00	3.13	2.65	2.74	2.85	3.48	2.92	3.03	2.63	2.57	2.67	2.51
0.28	0.28	0.25	0.32	0.29	0.31	0.31	0.30	0.30	0.23	0.30	0.27	0.337	0.34	0.33	0.34
0.27	0.27	0.36	0.17	0.43	0.48	0.15	0.19	0.15	0.45	0.19	0.25	0.09	0.08	0.10	0.11
99.51	99.25	98.77	99.69	99.55	99.17	99.82	99.52	99.16	99.34	99.77	98.84	99.22	99.59	100.13	99.69
99.0	65.3	73.8	119.6	80.2	106.0	80.0	94.0	77.1	131.0	111.6	110.2	78	66.5	70.0	62.0
732.3	719.8	632.5	717.6	790.5	790.3	842.3	807.5	783.9	642.6	778.9	687.4	823	887.6	808.7	863.3
988.0	1036.4	1001.3	965.5	995.0	1127.6	1009.5	982.6	1033.2	1102.5	1030.8	992.7	998	990.6	1004.4	969.4
9.6	9.2	8.6	7.8	9.5	9.3	10.3	10.2	10.0	7.7	10.2	9.0	9.7	8.9	9.2	9.3
123.3	120.5	104.2	111.2	125.0	119.7	132.4	128.8	132.8	84.0	125.2	115.4	144	135.5	138.7	139.6
37.3	26.9	32.9	29.7	44.0	36.3	59.3	53.4	30.6	20.1	23.1	33.0	43.1	39.3	38.1	39.3
15.3	15.4	13.2	14.9	15.6	15.0	18.1	18.3	16.7	12.8	16.8	14.7	19.3	16.9	18.0	17.4
23.4	20.3	20.9	22.5	24.0	23.0	34.3	33.5	26.3	18.6	22.3	23.2	27.6	24.1	24.5	25.3
13.0	12.8	12.7	12.0	12.7	12.7	12.2	12.5	12.9	12.5	13.3	12.6	13.8	9.6	9.5	9.8
120.3	120.0	83.9	12.3	109.7	129.5	121.3	111.9	130.7	64.6	126.1	106.8	148	131.2	139.4	132.9
8.3	7.4	8.3	7.6	7.8	8.8	7.4	7.4	7.3	8.6	7.6	8.2	7.7	6.7	7.4	6.2
36.1	35.5	38.6	37.2	37.0	41.0	34.0	34.4	35.9	38.1	36.5	35.5	34.4	35.2	35.1	34.9
73.5	74.9	77.3	79.6	74.8	83.9	68.6	74.1	75.7	76.4	77.0	76.3	70.4	71.5	74.3	71.6
32.8	32.2	31.9	34.7	32.3	35.4	32.6	31.4	33.1	31.4	33.6	32.0	32.3	32.7	33.2	32.3
5.9	5.6	5.9	6.4	5.7	6.2	5.8	5.8	6.1	5.8	5.9	5.6	5.8	5.6	5.7	5.2
1.4	1.4	1.2	1.5	1.4	1.4	1.5	1.5	1.5	1.2	1.4	1.3	1.27	1.4	1.3	1.4
4.1	3.8	3.8	4.2	4.1	4.0	4.2	3.6	4.3	3.9	4.1	3.9	4.5	4.3	4.4	4.1
2.4	2.4	2.3	2.5	2.4	2.3	2.3	2.4	2.3	2.2	2.5	2.4	2.5	2.2	2.2	2.2
1.1	1.0	1.0	0.9	0.9	0.8	1.2	1.0	1.0	0.9	1.0	1.1	0.6	1.0	1.1	1.1
1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	1.0	0.9	1.0	0.9	0.98	0.9	0.9	0.9





**Amphibole**

b)



SEM 3

