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4 **The eruptive chronology of the Yucamane-Calientes compound volcano:**
5 **a potentially active edifice of the Central Andes (southern Peru)**
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35 **Abstract**

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37 We reconstruct the eruptive chronology of the Yucamane–Calientes compound volcano in
38 southern Peru based on extensive fieldwork and a large dataset of geochronological (K-Ar,
39 ⁴⁰Ar/³⁹Ar, **U-Pb**, and ¹⁴C) and geochemical (major and trace element) analyses. This
40 compound volcano is composed of two edifices that have experienced discontinuous volcanic
41 activity from the middle Pleistocene to the Holocene. The Calientes volcano has been
42 constructed in four successive stages: Calientes I is composed of andesitic lava flows dated at
43 ~500 ka. Subsequently, the Callazas ignimbrite (Calientes II stage) was emplaced ~160-190
44 ka, followed by the main cone-building stage (Calientes III) at ~130-100 ka. Finally, the
45 Holocene Calientes domes were emplaced and represent the last eruptive products of this
46 edifice. The Yucamane volcano has been constructed in three stages: Yucamane I consists of
47 a succession of andesitic lava flows exposed at the base of the volcano that are older than 40
48 ka. Yucamane II (~36-30 ka) comprises a thick sequence of block-and-ash-flow deposits that
49 represents an episode of dome growth predating the younger Yucamane cone (Yucamane III)
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123 69 Sabancaya. In addition, these two volcanoes display on-going eruptions that began in 2015
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125 70 CE at Sabancaya and 2019 CE at Ubinas.

126
127 71 Reconstructing the eruptive chronology of a potentially active volcano represents a
128
129 72 key step for hazard assessment. During the last decades, the eruptive chronologies of El Misti
130
131 73 (Thouret et al., 2001), Ubinas (Thouret et al., 2005), and Ampato-Sabancaya (Samaniego et
132
133 74 al., 2016) have been investigated in detail. However, little is known about other volcanic
134
135 75 centers such as Yucamane-Calientes (Rivera and Mariño, 2004), a young-looking edifice
136
137 76 located 7-8 km NE of Candarave in Tacna Province, southern Peru (Fig. 1b, c). The volcano
138
139 77 is situated on a gently inclined plateau, bounded by the Calientes and Callazas rivers to the
140
141 78 east and west, respectively. Small villages on this plateau are located at 8 to 20 km south of
142
143 79 Yucamane's summit (Fig. 1). The total population living in a radius of 20 km of this volcanic
144
145 80 center is roughly estimated at 8,000 inhabitants (INEI, 2018).

146
147 81 We undertook a comprehensive volcanological study of the Yucamane-Calientes,
148
149 82 including detailed fieldwork coupled with geochronological and geochemical analyses to
150
151 83 reconstruct the structure and eruptive chronology of this compound volcano from the Middle
152
153 84 Pleistocene to Holocene. Based on these data, we propose that Yucamane-Calientes consists
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155 85 of two adjacent edifices with contrasting morphologies and eruptive styles, both active
156
157 86 through the Holocene.

158 87

159 88 **2. Geological setting**

160
161 89 The Yucamane-Calientes compound volcano (YCCV, 15°49.3'S, 71°52.7'W) is
162
163 90 constructed on the Mesozoic and Cenozoic volcanic and sedimentary formations that compose
164
165 91 the Western Cordillera of the Peruvian Andes (Sévrier and Soler, 1991). At the latitude of the
166
167 92 YCCV, the cordillera is made of Jurassic to Cretaceous sandstones and carbonaceous shales
168
169 93 of the Labra and Hualhuani Formations covered by the Toquepala Formation, a Cretaceous
170
171 94 volcanic sequence (De la Cruz and De la Cruz, 2000). Overlying these units are the volcanic
172
173 95 and volcano-sedimentary sequences of the Tacaza Group and the Huaylillas Formation.
174
175 96 Regional studies propose ages in the range of 30-24 Ma for the Tacaza Group (Mamani et al.,
176
177 97 2010; Thouret et al., 2016), whereas in the region of the YCCV, the ignimbrites of the
178
179 98 Huaylillas Formation have been dated by the K-Ar method at 24-10 Ma (Tosdal et al., 1981;
180
181 99 Quang et al., 2005). At the top of the sequence, several eroded composite cones belonging to
182
183 100 the Barroso Group (10-1 Ma, Mamani et al., 2010) are exposed near the YCCV, including
184
185 101 Nazaparco, San Pedro, and Lopez Extraña volcanoes (Fig. 2). A lava sample from the

181
182
183 102 Nazaparco volcano yielded a whole-rock K-Ar age of 5.6 ± 0.2 Ma (Martínez and Cervantes,
184 103 2003).

186 104 Two major fault systems cross this part of the Andean cordillera. The main system is a
187 105 series of NW-SE-trending normal faults with a sinistral component that are roughly parallel to
188 106 the Andean front (Martínez and Cervantes, 2003; Benavente et al., 2010). Near the YCCV,
189 107 these faults are several kilometer-long structures extending through the valleys of the
190 108 Tacalaya and Callazas rivers. These structures affect the Quaternary volcanoes and control
191 109 their structural development (cf. Samaniego et al., 2015). The secondary NE-SW fault system
192 110 is represented by local normal faults that control the geothermal surface manifestations,
193 111 especially those of the Salado and Calientes rivers.
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201 113 3. Methodology

202 114 Due to the extremely arid weather conditions of the Central Andes, the volcanic
203 115 deposits of the YCCV are well preserved. Fieldwork between 2012 and 2014 included
204 116 geological mapping and sampling of most stratigraphic units, resulting in a broad suite for
205 117 petrographic, geochemical, and geochronological studies. Major- and trace-element whole-
206 118 rock analyses were obtained at the Laboratoire Géosciences Océan (IUEM-UBO, Brest,
207 119 France) from agate-crushed powders of 63 samples spanning the entire volcanic history. We
208 120 used an Inductive Coupled Plasma-Atomic Emission Spectrometer (ICP-AES), following the
209 121 analytical procedure described by Cotten et al. (1995). Additional information concerning the
210 122 geochemical data methods is shown in the Supplementary Material 1.
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217 123 The chronology of the Pleistocene eruptive activity was established using the unspiked
218 124 K-Ar dating method described in Guillou et al. (2011). Nine samples collected from the main
219 125 stratigraphic units that encompass the entire history of the volcanic complex were selected for
220 126 K-Ar dating (Table 1). Additionally, an ignimbrite and three lava samples were dated using
221 127 the $^{40}\text{Ar}/^{39}\text{Ar}$ technique applied on plagioclases, which are ubiquitous crystals in the samples
222 128 (Table 2). The corresponding analytical procedures are described in the Supplementary
223 129 Material 1. ArArCalc software (Koppers, 2002) was used to calculate isochron regressions,
224 130 weighted mean ages, and probability of fit estimates. Criteria defining isochron ages are
225 131 described in Sharp and Renne (2005). $^{40}\text{Ar}/^{39}\text{Ar}$ ages are summarized in Table 2 and detailed
226 132 in Supplementary Material 2. In addition, U-Pb age determinations on zircons were obtained
227 133 at Laboratoire Magmas et Volcans (Clermont-Ferrand, France) on two samples from the same
228 134 ignimbrite unit. Previously established analytical techniques (Hurai et al., 2010; Paquette et
229 135 al., 2014) were adapted to Pleistocene volcanic samples (Paquette et al., 2019). Common Pb
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243 136 as well as $^{230}\text{Th}/^{238}\text{U}$ and $^{231}\text{Pa}/^{235}\text{U}$ disequilibria were corrected according to the methods
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245 137 published by [Sakata et al. \(2017\)](#) and [Sakata \(2018\)](#).

246 138 The Late Pleistocene and Holocene chronology of the volcanic activity was
247
248 139 constrained by 5 new radiocarbon ages obtained from charcoal samples collected in
249
250 140 pyroclastic deposits. These samples were analyzed at the Centre for Isotope Research (CIO),
251
252 141 Groningen University (Netherlands). [Table 3](#) gives the conventional ^{14}C ages ($\pm 1\sigma$), and the
253
254 142 calibrated ages ($\pm 1\sigma$ and 2σ). Conversion from conventional ^{14}C ages to calendar ages was
255
256 143 carried out using the Calib 7.1 code ([Stuiver and Reimer, 1993](#); [Stuiver et al., 2005](#)) and the
257
258 144 Southern Hemisphere calibration curve (SHCal13, [Hogg et al., 2013](#)), which is applicable up
259
260 145 to 50,000 cal BP.

261 146 The volcano's morphometric parameters (volcano basal area, height, and volume)
262
263 147 were obtained using the methodology of [Grosse et al. \(2014\)](#). Based on a 6-m digital elevation
264
265 148 model (obtained from a Spot satellite image processed by INGEMMET's geomatic service)
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267 149 and the edifice external outline obtained from the geological map ([Fig. 2](#)), we computed the
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269 150 substratum topography by applying different interpolation techniques (linear, cubic, inverse
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271 151 distance weighting method). Taking this topographic surface as a reference, we determined
272
273 152 the volcano's maximum height and volume.

272 154 **4. Morphology and structure**

273 155 We propose that the YCCV is composed of two adjacent edifices with contrasting
274
275 156 morphologies and eruptive styles ([Figs. 2, 3](#)). Calientes volcano (4980 m above sea level, m
276
277 157 asl) is at the northern part of the massif, while Yucamane volcano (5495 m asl) is located to
278
279 158 the south. Lavas from the lower cone of Yucamane overlap those of the southern flank of
280
281 159 Calientes. The YCCV covers an area of 58-60 km² and has an estimated volume of 20-25
282
283 160 km³. This bulk volume includes moraine deposits, with a volume estimated at 0.5-1 km³ and a
284
285 161 conspicuous ignimbrite deposit emplaced at the west and southwest foot of Calientes and
286
287 162 south foot of Yucamane with a bulk volume estimated at 8-12 km³ (see below). Both
288
289 163 volcanoes are constructed to the south of the highly eroded Yucamane Chico edifice ([Figs. 2,](#)
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291 164 [3](#)).

292 165 Calientes is a composite cone rising from 4300 to 4980 m asl with an asymmetric
293
294 166 morphology composed of a succession of overlapping lava flows and a truncated summit with
295
296 167 a 1 km-wide crater open toward the SE ([Figs. 2, 3](#)). A well preserved, 1 km-wide, 500 m-high
297
298 168 dome complex fills the mouth of the topographic depression. Although the lower and middle
299
300 169 slopes of Calientes display ample evidence of glacial erosion, the summit zone and the dome

301
302
303 170 complex lack such evidence, suggesting a post-glacial (Holocene) age. **Yucamane** is a steep-
304
305 171 sided, symmetrical composite cone with a roughly circular base (6-8 km in diameter) and a
306
307 172 generally less eroded morphology than Calientes. It rises from 3800 to 5495 m asl. In the
308
309 173 lower part of the cone, lava flows have slopes from 5-15°, while lava flows above 4800 m asl
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311 174 have steep slopes (>25°) (Fig. 3). The volcano is formed by interlayered lava flows and some
312
313 175 pyroclastic deposits defining a **1200-m-high** cone. Lavas from the middle and lower flanks
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315 176 have been impacted by Pleistocene glaciations and are locally covered by moraine deposits.
316
317 177 The edifice's summit is composed of two nested craters of 600 and 350 m in diameter, the
318
319 178 innermost of which is ~120 m deep. The crater is partially filled by reworked tephra deposits
320
321 179 and its inner walls are relatively gently sloping with pervasive fumarolic activity. The eastern
322
323 180 foot of the YCCV is a plateau characterized by gentle slopes (<10°) (Figs. 2, 3) and covered
324
325 181 by younger tephra-fall deposits.

322 182 The morphology of the YCCV was shaped by late Pleistocene glaciations. As a result,
323
324 183 moraine deposits are mapped on the western and southern flanks (Fig. 2). These moraines
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326 184 have elongate shapes, heights of tens of meters, and lengths of hundreds of meters. By
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328 185 comparison with other Late Pleistocene Peruvian volcanoes, such as Coropuna (Bromley et
329
330 186 al., 2009), Ampato (Samaniego et al., 2015) and Hualca Hualca (Alcalá-Reygosa et al., 2017),
331
332 187 we suggest that these moraines were emplaced during the Last Glacial Maximum (LGM)
333
334 188 which was roughly dated at 16-25 ka in this part of the Andes (Bromley et al., 2009; Zech et
335
336 189 al., 2009). At a regional scale, smaller glacial re-advances such as the Younger Dryas event
337
338 190 (10-12 ka; Clapperton, 1993) and other minor Holocene glacial fluctuations (cf. Jomelli et al.,
339
340 191 2011) have also been identified, but we found no evidence of such glacial advances at YCCV.

340 193 **5. The eruptive chronology of Yucamane-Calientes compound volcano (YCCV)**

341 194 The following description of the volcanic units of Calientes and Yucamane edifices
342
343 195 (Fig. 2) is based on our morphologic, **stratigraphic**, and geochronological data.

346 197 **5.1. Yucamane Chico lavas**

348 198 The older volcanic units of the YCCV rest on top of lavas from Yucamane Chico
349
350 199 volcano (6025 m asl), which is located immediately north of the YCCV and is an old and
351
352 200 highly eroded edifice displaying a similar degree of erosion as the Barroso Group volcanoes
353
354 201 (i.e. Nazaparco). Yucamane Chico is elongated in the WNW-ESE direction, with a steep-
355
356 202 sided southern flank (Fig. 3). Its lava flows have a porphyritic texture with a mineral
357
358 203 assemblage of plagioclase, clinopyroxene, orthopyroxene, Fe-Ti oxides, and minor amphibole

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362
363 204 phenocrysts, embedded within an aphanitic groundmass. An andesitic lava flow from the base
364
365 205 of the eastern flank is dated at 5.47 ± 0.09 Ma, whereas another andesitic lava that crops out
366
367 206 below the base of the Yucamane cone yielded an age of 6.14 ± 0.11 Ma (samples YU-12-22
368
369 207 and YU-13-16 respectively, Table 1). These ages are in good agreement with the ages
370
371 208 reported for lavas from the neighboring Nazaparco edifice (Martínez and Cervantes, 2003)
372
373 209 and confirm a Mio-Pliocene age for Yucamane Chico.

374 211 5.2. Calientes I

376 212 The oldest remnants of the Calientes edifice are sub-horizontal lava flows that crop out
377
378 213 on the lower western flank of the volcano (Figs. 2, 3). This succession is composed of 20-60
379
380 214 m-thick, andesitic (60.9-61.9 wt.% SiO₂) lava flows resting discordantly on older lavas from
381
382 215 the Yucamane Chico edifice and volcanic products from the Plio-Quaternary volcanic
383
384 216 formations. A sample collected from a lava flow of this unit has been K-Ar dated at 493 ± 9
385
386 217 ka (sample YU-12-50, Table 1).

387 219 5.3. Calientes II: the Callazas Ignimbrite

389 220 **Deposits' description.** South of Yucamane volcano, conspicuous ignimbrite deposits crop out
390
391 221 at the foot of the western and southwestern flanks of Calientes (Figs. 2, 3). These deposits
392
393 222 cover the older formations composed of sedimentary and volcanic rocks from Labra and
394
395 223 Huaylillas formations, as well as the lavas from the older Calientes I unit. The ignimbrite
396
397 224 deposits compose the plateau located between the Callazas and Salado rivers, reaching
398
399 225 Laguna Aricota 20 km to the south of Yucamane's crater (Fig. 2). They are structureless,
400
401 226 slightly consolidated, grey to beige in color, and have local maximum thicknesses of 80-100
402
403 227 m. The total reconstructed area of the deposit is ~ 165 km² with a minimum volume in the
404
405 228 range of 8-12 km³. The deposit's pumices are amphibole-bearing dacites (66-68 wt.% SiO₂),
406
407 229 representing the most silicic composition of the YCCV.

408 230 In the proximal zone (e.g. San Lorenzo, western flank, Fig. 3) at <6-8 km from
409
410 231 Yucamane summit, the ignimbrite deposit is composed of at least six sub-horizontal pumice-
411
412 232 rich layers, with individual thicknesses of 6-12 m. The lower part of the succession is well
413
414 233 consolidated with incipient welding and deformed pumice fragments. The middle part of the
415
416 234 succession consists of lag breccia layers composed of angular to subangular accidental lithic
417
418 235 fragments up to 60 cm in diameter, suggesting proximity to the vent area. The upper part of
419
420 236 the succession is >10 m of non-consolidated surge deposits with centimetric, planar, and
237 cross-bedded stratification.

421
422
423 238 In the medial and distal zones, 6-8 km from the Yucamane volcano, at least three sub-
424
425 239 units are exposed. The ignimbrite deposits at these zones are structureless, with a total
426
427 240 thickness of 40-60 m. The lower level is poorly consolidated, while the middle level is more
428
429 241 consolidated, with crude columnar jointing (Fig. 3). The lower and middle layers are grey to
430
431 242 whitish-grey, whereas the upper level is yellowish. Pumice as large as 25 cm in diameter are
432
433 243 present 20 km from the YCCV. In the distal zone, close to Callazas river valley, the
434
435 244 ignimbrite deposits are covered by a succession of block-and-ash-flow deposits. We stress
436
437 245 that no marked erosion surface has been observed.
438
439 246

439 247 **Age determination.** The Callazas Ignimbrite was dated using the $^{40}\text{Ar}/^{39}\text{Ar}$ method on
440
441 248 plagioclases and U-Pb method on zircons. Both methods are described in [Supplementary](#)
442
443 249 [Material 1](#). The results of $^{40}\text{Ar}/^{39}\text{Ar}$ dating of sample YU-12-78A are presented as probability
444
445 250 diagrams (Deino and Potts, 1990) and inverse isochrones in Fig. 4. A total of 15 populations
446
447 251 of 1 to 2 crystals were analyzed. Individual $^{40}\text{Ar}/^{39}\text{Ar}$ ages range between 126.6 ± 56.3 and
448
449 252 583.7 ± 117.6 ka (Supplementary Material 2). Such scatter may reflect argon loss for the
450
451 253 youngest ages and the presence of excess argon and/or antecrysts for the oldest ages. In fact,
452
453 254 plagioclase phenocryst in this sample displays two families: the dominant group corresponds
454
455 255 to euhedral, non-altered, zoned crystals; whereas the accessory group corresponds to sieve-
456
457 256 cored crystals with frequent dissolution internal zones. Following the definition of Jerram and
458
459 257 Martin (2008), we interpret the first group as phenocrysts mostly in equilibrium with the
460
461 258 groundmass, and the second group as antecrysts. A reasonable probability of fit (*i.e.* $p=0.42$)
462
463 259 coincides with a roughly Gaussian distribution centered at 198.4 ± 14.8 ka, which is the
464
465 260 weighted mean value of the 7 analyses remaining after eliminating the two subzero ages, the
466
467 261 youngest age, and the five oldest ages (Fig. 4a). Such a weighted mean age is likely
468
469 262 unaffected by excess argon. The corresponding $^{40}\text{Ar}/^{36}\text{Ar}$ initial intercept is 306.0 ± 8.1 ,
470
471 263 equivalent to the modern atmospheric ratio. The inverse isochron age (Fig. 4b) calculated
472
473 264 using the same population (170.7 ± 30.5 ka) is also equivalent at the 1σ level to the weighted
474
475 265 mean of the individual Ar-Ar ages. We apply the alteration index (AI) defined by Baksi
476
477 266 (2007), which is a measure of the extent of secondary alteration based on ^{36}Ar and ^{39}Ar
478
479 267 contents, to better constrain our data and check that the final age was calculated from
480
268 unaltered feldspars. Plagioclases are considered unaltered if their AI value is lower than
269 0.00006. AI values for the two plagioclases yielding subzero age grains are about three to four
270 times higher than the limit, suggesting that they experienced argon loss from alteration. We
271 infer that two additional crystals in the 420–580 ka age range with AI values 2 to 3 times

481
482
483 272 higher than the permitted threshold value experienced K loss during alteration resulting in
484
485 273 overestimated ages. Three other grains yielding old ages have AI values lower than the cutoff
486
487 274 value. We suggest that these unaltered old grains are xenocrysts. Based on these $^{40}\text{Ar}/^{39}\text{Ar}$
488
489 275 data, we retain the value of 198.4 ± 14.8 ka (YU-12-78A, Table 2) as the most probable
490 276 eruption age.

491 277 We also obtained U-Pb ages on selected populations of zircon from two samples from
492
493 278 the middle subunit (YU-13-07) and the upper surge deposits (YU-12-78A). In both samples,
494
495 279 we found similar zircons populations yielding ages corresponding to successive crystallization
496
497 280 episodes from ~ 460 ka to ~ 160 ka with a period of about 50 ka between each new episode
498
499 281 (Supplementary Material 3, Fig. 5). Zircon crystallizes in the magma reservoir prior to
500
501 282 eruption and consequently, they provide a maximum estimate for the eruption age. Based on
502
503 283 these data, we consider that the eruption age is close to 158 ± 20 ka and that the older zircons
504
505 284 are antecrysts, which were probably related to successive magma input into the reservoir.
506
507 285 Both methods yield statistically indistinguishable ages suggesting an eruption age between
508
509 286 158 ± 20 ka and 197 ± 16 ka (Fig. 5). These data are in agreement (within errors) with an
510
511 287 $^{40}\text{Ar}/^{39}\text{Ar}$ age (YU-12-02, 213.4 ± 13.5 ka, Table 2) obtained on a juvenile sample from a
512
513 288 block-and-ash-flow deposit covering the Callazas ignimbrite deposits.

512 290 5.4. Calientes III

513 291 The Calientes III unit predominantly comprises lavas of the middle and upper part of
514
515 292 the edifice between 4200 and 5374 m asl and represents the main cone-building stage of
516
517 293 Calientes. The unit consists of a ~ 1150 -1200 m-thick succession of andesitic and dacitic
518
519 294 (60.2 - 65.1 wt.% SiO_2), blocky lava flows. These lavas rest discordantly on remnants of the
520
521 295 Calientes I lavas and the Callazas ignimbrite (Figs. 2, 3), and extend as far as 8 km northwest
522
523 296 and 5 km southwest from the summit. The lavas are strongly affected by glacial erosion,
524
525 297 suggesting an age older than the LGM. This observation is confirmed by a K-Ar age of $126 \pm$
526
527 298 3 ka (YU-12-31, Table 1) and an $^{40}\text{Ar}/^{39}\text{Ar}$ age on plagioclase of 95.6 ± 16.7 ka (YU-12-44,
528
529 299 Table 2) obtained for two different lava flows above the Callazas ignimbrite deposits. As for
530
531 300 Callazas ignimbrite, a large amount of the $^{40}\text{Ar}/^{39}\text{Ar}$ dated feldspars are considered antecrysts,
532
533 301 only the three youngest and less radiogenic crystals were used to calculate the $^{40}\text{Ar}/^{39}\text{Ar}$ age
534
535 302 of this lava flow.

536 303 We include in this unit a succession of at least three block-and-ash-flow deposits
537
538 304 cropping out on the western side of the Salado river valley, 6-8 km from Yucamane's summit
539
540 305 (Figs. 2, 6) and overlying the Callazas ignimbrite deposit. Each layer is 12-18 m-thick, light

541
542
543 306 grey, structureless, unconsolidated, and **all** have gradational contacts between them. The
544
545 307 deposits contain 30-40 vol.% grey juvenile blocks of dacitic composition (63.0-65.9 wt.%
546 308 SiO₂) and 10-15 vol.% accidental lithic fragments in an ash-rich matrix. A juvenile block
547
548 309 from this block-and-ash-flow deposit was dated on plagioclase by ⁴⁰Ar/³⁹Ar at **133.4 ± 13.5 ka**
549
550 310 (YU-12-68B, [Table 2](#)). The ⁴⁰Ar/³⁹Ar experiment evidences that even in juvenile blocks older
551 311 crystals can be trapped. Indeed, only 8 of the 19 dated populations of feldspars are juvenile,
552
553 312 the others are xenocrystic,

554
555 313 Lastly, despite not being directly related with this eruptive stage, we include in this
556 314 unit a young lava dome (~900 m diameter and ~300 m high) mapped in the upper southern
557
558 315 flank of the Mio-Pliocene Yucamane Chico edifice. A lava sample from this dome yielded a
559 316 K-Ar age of **102 ± 6 ka** (YU-12-40, [Fig. 2](#); [Table 1](#)). The dome's position and age suggest that
560
561 317 different eruptive vents were active during the Calientes III stage.
562
563 318

564 319 **5.5. Calientes IV**

565 320 The uppermost flank of Calientes and a younger dome complex were constructed
566
567 321 during the last eruptive stage of Calientes. The viscous lavas, domes, and coulees of the upper
568
569 322 Calientes are cut by a SE-facing, relatively small (1 km-wide) amphitheater probably formed
570
571 323 by glacial erosion. The younger dome complex is situated SE of the amphitheater ([Figs. 2, 3](#))
572 324 and is composed of at least three coalescent lava domes emplaced during a likely long-lasting
573
574 325 extrusive event. They extend approximately over a diameter of 1.2 km and height of 600 m.
575 326 These domes consist of porphyritic dacites (63-64 wt.% SiO₂). The fresh morphology and the
576
577 327 lack of glacial erosion of these domes suggest that they were emplaced during the Holocene.
578
579 328 A lava sample from the dome complex, which comes from the SW upper flank of Calientes
580 329 yielded a sub-zero K-Ar age of **3 ± 3 ka** (YU-14-16, [Table 1](#)), supporting a Holocene age.
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582 330

583 331 **5.6. Yucamane I**

584 332 The older remnants of Yucamane consist of a **300-m-thick** succession of andesitic
585
586 333 and dacitic (58.5-64.7 wt.% SiO₂), blocky lava flows ([Figs. 2, 3](#)) that crop out on the southern
587
588 334 flank of the cone and discordantly overly the upper Miocene-Pleistocene products of
589
590 335 Yucamane Chico. Samples from Yucamane I stage lavas did not yield meaningful ages
591 336 because atmospheric contamination was too high to allow detection of ⁴⁰Ar*. Field
592
593 337 relationships, nevertheless, support an age younger than the Calientes III stage (i.e. < 100 ka).
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595 338

596 339 **5.7. Yucamane II**

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602
603 340 A thick succession of a directed blast, a debris **avalanche**, and at least two block-and-
604
605 341 ash-flow deposits overlies the basal lava flows of the Yucamane cone. Such deposits reflect a
606
607 342 voluminous dome-forming eruptive stage after the Yucamane sector collapse.
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609 343

610 344 **5.7.1. Andesitic directed blast deposit.** This unit forms a conspicuous layer that crops out to
611 345 the west and south of Yucamane volcano, covering a lobe-shaped area of ~130-135 km² (Figs.
612 346 6, 7). Based on the observed maximum thickness of this deposit, we infer a southwestern
613 347 dispersion axis. The deposit is grey in color, unconsolidated, and its thickness decreases at a
614 348 relatively constant rate. The deposit is well sorted, fines-depleted, and mainly composed of
615 349 dense, lapilli-size juvenile blocks (40-50 **vol.%**), and accidental lithic fragments (20-30
616 348 vol.%). The juvenile fragments are homogeneous porphyritic andesites (62.3-62.7 wt.%
617 349 SiO₂).
618 350
619 351

622 352 In the proximal areas, less than 8 km south and southwest of Yucamane's crater (i.e.
623 353 Quebrada Honda and Curancurane ravines, Fig. 6), the deposit's thickness ranges between 1
624 354 and 5 m, and the juvenile blocks have a maximum diameter of 40 cm. In Quebrada Honda, the
625 355 deposit overlies an unconsolidated andesitic block-and-ash-flow deposit whereas at Quebrada
626 356 Curancurane, the deposit overlies the Callazas ignimbrite deposit (Fig. 6). In medial zones, for
627 357 example near the town of Yucamane, 9 km south of Yucamane's crater, the deposit overlies
628 358 the Salado block-and-ash-flow deposits, and underlies the Campanani block-and-ash-flow
629 359 deposits (see below). No paleosol or erosive contact has been observed at that place. In distal
630 360 areas more than 12 km to the west and southwest of Yucamane's summit (i.e. Pampa Coirire,
631 361 and the town of San Pedro, Fig. 2), the deposit has a thickness between 30 and 80 cm. In such
632 362 areas, the deposit includes dense porphyritic juvenile blocks with a maximum diameter of 12
633 363 cm. The presence of the deposit in such distal sites implies that the pyroclastic density current
634 364 would have crossed the deep Callazas valley. A ¹⁴C date from charcoal collected from the
635 365 deposit 11 km west from Yucamane's crater yielded an uncalibrated age of 36,450 ± 260 BP
636 366 (**sample YU-13-20, Table 3**).
637 367

646 367 We interpret this layer as a lateral blast deposit based on its sedimentological
648 368 characteristics, abundance of dense juvenile dacitic fragments, lobe-shaped distribution in a
649 369 narrow sector to the south of YCCV, and progressive thickness decrease without any
650 370 topographic control. We suggest that the deposit was emplaced by such a dilute pyroclastic
651 371 density current when a growing lava dome collapsed and subsequently exploded (i.e.,
652 372 Soufrière Hills 1997; Voight et al., 2002; Belousov et al., 2007).
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663 374 **5.7.2. Debris-avalanche deposit.** The deposit crops out between 3 and 14 km south and
664
665 375 southeast from Yucamane's crater, near the town of Santa Cruz and in the Mal Paso and
666
667 376 Pampa Pajonal sectors (Fig. 3). In the latter site, the deposit forms hummocky topography.
668
669 377 The debris-avalanche deposit is a structureless 40-60 m-thick unit overlying the Callazas
670
671 378 ignimbrite. In most locations, the debris-avalanche deposit displays a block-rich facies
672
673 379 composed of heterogeneous, dense, sub-angular lava blocks (58-62 wt.% SiO₂) that are tens
674
675 380 of centimeters to meters in diameter. Some blocks have typical jigsaw-like fractures. Locally,
676
677 381 however, the deposit displays a matrix-rich facies containing small fragments of porphyritic
678
679 382 lava blocks dispersed in a sandy matrix.

680
681 383 At Quebrada Curancurane, 6 km west of Yucamane, the debris-avalanche deposit is
682
683 384 over 8 m thick (Fig. 6). The deposit contains dense lava blocks of heterogeneous
684
685 385 compositions and up to 3 m diameter within a matrix composed of sand and gravel. Most
686
687 386 blocks have characteristic jigsaw fractures. At this site, the debris-avalanche deposit directly
688
689 387 overlies the blast deposit. Such observation, together with the petrographic and geochemical
690
691 388 similarities between the debris avalanche blocks and those of the subsequent block-and-ash-
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693 389 flow deposits, support a "comagmatic" origin for both deposits and implies that the debris-
694
695 390 avalanche deposit originated from the collapse of a voluminous dome complex.

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697 391
698
699 392 **5.7.3. Campanani block-and-ash-flow deposit.** The unit crops out in almost all ravines on
700
701 393 the south and southwestern flanks of Yucamane (Fig. 7). In the lower part of Quebrada
702
703 394 Campanani, near the town of Yucamane Pampa (9 km southwest of Yucamane's crater) and
704
705 395 in Quebrada Honda (9 km south of Yucamane's crater), the deposit is 1-8 m thick, and
706
707 396 composed of an ash-rich matrix with angular, andesitic blocks (62-63 wt.% SiO₂) that are tens
708
709 397 of centimeters to a meter in diameter. The deposit is grey, structureless, slightly consolidated,
710
711 398 and overlies the blast deposit (Fig. 7). The contact between the blast and the Campanani
712
713 399 deposits is gradational.

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715 400
716
717 401 **5.7.4. Honda block-and-ash flow deposit.** In the Quebrada Honda, 9 km south of
718
719 402 Yucamane's crater another block-and-ash-flow deposit crops out, which has an average
720
721 403 thickness of 10-12 m (Fig. 6). This reddish grey deposit is structureless and slightly
722
723 404 consolidated. It overlies a thin (20-40 cm thick) unconsolidated ash-flow deposit that covers
724
725 405 the Campanani block-and-ash-flow deposit. In the middle and upper parts of the sequence, the
726
727 406 deposit is slightly reversely graded. The unit's matrix of coarse ash and lapilli composes 60-
728
729 407 70 vol.% of the deposit with dense juvenile blocks (up to 1 m in diameter) forming the

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722
723 408 remaining 30-40 vol.%. The juvenile blocks are andesitic in composition (61-62 wt.% SiO₂).
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725 409 Charcoal from the base of the deposit at a site 8.5 km west of Yucamane's crater yielded an
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727 410 uncalibrated age of 29,200 +170/-160 BP (sample YU-14-11, Table 3). The deposit also
728
729 411 crops out in other ravines at the foot of Yucamane's south flank, such as Quebrada
730
731 412 Campanani where it is at the top of the pyroclastic succession. The succession is covered by at
732
733 413 least six lahar deposits with thicknesses of 10-15 m. Due to the estimated volume of this
734
735 414 succession of block-and-ash-flow deposits (0.08-0.11 km³), we infer that a significant dome-
736
737 415 forming phase followed the Yucamane sector collapse.
738

739 417 **5.8. Yucamane III**

740 418 **5.8.1. Cone-forming lava flows.** These lavas form Yucamane's upper cone between 4300
741 419 and 5508 m asl (Figs. 2, 3). The overlapping lava flows generally have slopes up to 30-40°
742
743 420 and maximum run-out distances of 4 to 5 km from Yucamane's crater. The lavas have
744
745 421 basaltic-andesite and andesite compositions (55.2-63.6 wt.% SiO₂). A lava sample from the
746
747 422 lower western flank was K-Ar dated at 23 ± 1 ka and a second sample from one of the
748
749 423 uppermost lava flows yielded a K-Ar age of 7 ± 1 ka (samples YU-12-61 and YU-12-27
750
751 424 respectively, Fig. 2 and Table 1). A third sample collected from a lava flow on the lower
752
753 425 southeast flank yielded a K-Ar age of 3 ± 2 ka (YU-12-16, Table 1). This latter lava flow is
754
755 426 overlain by a younger pumice lapilli tephra fall deposit from Yucamane (see below). Such
756
757 427 lava flow activity is in sharp contrast with the volcano's previous dome-collapse activity.
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759 428
760 429 **5.8.2. Scoria-flow deposits.** The deposits crop out on the lower southwestern and southern
761
762 430 flanks of Yucamane (Figs. 8, 9). They have a thickness of 10 m and are structureless, non-
763
764 431 consolidated, and have a gray-brown, sandy matrix. The deposits have 20-30 vol.% of blocks
765
766 432 and bombs (up to 60 cm in diameter) and 10-20 vol.% of dense lithic fragments. Scoria blocks
767
768 433 and bombs are basaltic-andesite to andesite in composition (56.7-58.4 wt.% SiO₂). At
769
770 434 Quebrada Gentilcahua (Fig. 2), the deposits overlie older lava flows of Yucamane's cone as
771
772 435 well as the Campanani block-and-ash-flow deposit. To the south, in Quebrada Condorcahua
773
774 436 the sequence comprises at least three scoria-flow units with gradational contacts between
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776 437 them that are covered by a 1.5-2.0 m-thick pumice-rich lahar deposit (Figs. 7, 8). This
777
778 438 sequence of scoria-flow deposits was emplaced during a period of large explosive eruptions at
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780 439 Yucamane, which probably occurred in the late Pleistocene or early Holocene (see below).
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781
782
783 441 **5.8.3. Scoria-rich tephra-fall deposits.** Three scoria-rich tephra-fall deposits crop out on
784
785 442 Yucamane's lower south and southeast flanks. Based on the deposits distribution and decrease
786
787 443 in thickness, the deposits have a dispersion axis to the southeast (Vela, 2015). These tephra-
788
789 444 fall deposits overly moraines, which are probably associated with the LGM.
790 445

791 446 **Lower "Halloween" tephra-fall deposit.** At Mal Paso hill (4 km from Yucamane's summit),
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793 447 this deposit is 12-15 cm thick, whereas it is 8-10 cm thick in the Hueltajavira sector, which is
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795 448 6-7 km from the crater (Figs. 8c, 9). The deposit is slightly **inversely** graded and characterized
796
797 449 by a mix of oxidized scoria fragments with an intense orange patina and dark gray, fresh
798
799 450 basaltic-andesite (53.9 wt.% SiO₂) scoria. Both scoria types compose 60 vol.% of the deposit
800
801 451 with the remaining volume composed of dense, grey, **aphanitic**, and porphyritic andesitic
802
803 452 lithic fragments. At 4 km southeast of the crater, the scoria **clasts** are less than 4 cm in
804
805 453 diameter, while the lithic fragments are less than 3.5 cm.

806 455 **"Parda" tephra-fall deposit.** At Mal Paso hill, the deposit is 16-18 cm thick (Figs. 8d, 9) and
807
808 456 crops out above the Lower Halloween deposit. It also crops out in Quebrada Honda, 9 km
809
810 457 south of the volcano, intercalated into the middle of the sequence of lahar deposits covering
811
812 458 the Honda block-and-ash-flow deposits. The Parda deposit is slightly **inversely** graded at its
813
814 459 base and slightly normally graded at the top. The proportion of both scoria and lithic
815
816 460 fragments is ~50 vol.% each. The andesite (56.6-57.4 wt.% SiO₂) scoria fragments are grey
817
818 461 with a light-to-medium brown patina and <3 cm in diameter at 4 km from the crater. At the
819
820 462 base and top of the deposit, grey, altered lithic lava fragments of **sub-centimeter** size are
821
822 463 **predominant**.

823 465 **Upper "Halloween" tephra-fall deposit.** In the area around Mal Paso hill, the deposit has a
824
825 466 thickness of 12-22 cm (Figs. 8b, 9) and crops out above the Parda and Lower Halloween
826
827 467 tephra-fall deposits. The deposit is composed of basaltic-andesitic to andesitic (55.5-56.4
828
829 468 wt.% SiO₂), slightly vesiculated scoria (60-70 vol.%) and dense lithic (30-40 vol.%)
830
831 469 fragments. It is characterized by the presence of altered scoria fragments with a characteristic
832
833 470 orange patina, especially in the lower and middle parts of the deposit. At its base, the deposit
834
835 471 is slightly **inversely** graded, while its top is slightly normally graded. At the layer's top,
836
837 472 abundant grey, lithic lava fragments of centimeter to millimeter scale are present. At 4 km
838
839 473 from the crater, the maximum size of the scoria measured is 4 cm and the maximum size of
840
474 the lithic fragments measured is 3 cm.

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843 475
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845 476 **5.8.4. The deposits of the more recent explosive eruptions.** On the lower eastern flank of
846 477 Yucamane two conspicuous deposits crop out, and are related to Yucamane's more recent
847 478 explosive activity.
848
849
850 479

851 480 **Pumice lapilli fall deposit.** On the plateau located between the cone and the Salado river
852 481 (Figs. 2, 10) a tephra-fall deposit composed of pumice and lithic lapilli crops out. The
853 482 deposit's thickness decreases from >50 cm in proximal areas 2-3 km from the crater to <5 cm
854 483 in medial to distal locations 8-9 km southeast of the crater (Fig. 11). The pumice fragments
855 484 are yellow grey in color and have an andesitic composition (61.1-62.7 wt.% SiO₂). The
856 485 pumice's maximum diameter decreases from 6.8 cm in the proximal zone to 2.5 cm in distal
857 486 areas. The lithics are composed of fresh (grey) and altered (brown and red) lava fragments
858 487 that decrease in size from 6 cm in the proximal zones to 1.5 cm in distal locations.

864 488 In the proximal and medial sectors, this deposit shows three distinct layers. The lower
865 489 layer is 6 cm thick in the proximal sector and <1 cm thick in the medial sector. It is composed
866 490 of dark ash dominated by fresh lava fragments. The lithics are 0.5-0.6 cm in diameter. The
867 491 lower layer is **inversely** graded and well sorted. The middle layer is up to 28 cm thick in the
868 492 proximal sector and gradually decreases to 6 cm in distal zones. The pumice lapilli are
869 493 angular to subangular and highly vesiculated. The layer's lithics are dark grey, non-altered,
870 494 aphanitic lava fragments. Some hydrothermally-altered lava fragments with a brown to red or
871 495 yellow color are also present. The layer is **inversely** graded and well sorted. The upper layer
872 496 is up to 21 cm thick in the proximal zone and gradually decreases to 10 cm thick.
873 497 **Hydrothermally altered** lithics are present in a lesser proportion than **in** the middle layer. The
874 498 upper layer is structureless and well sorted. The deposit only crops out sporadically in areas
875 499 **>10 km from** the volcano. A charcoal fragment collected in a fine-grained deposit at the base
876 500 of the pumice lapilli fall deposit (sample YU-13-15, Table 3) yielded a ¹⁴C age of **3,085 ± 35**
877 501 BP. Given that no **paleosol exists** below the tephra-fall deposit, we interpret this layer and the
878 502 overlying tephra-fall deposit as corresponding to the same eruptive event. We should stress
879 503 that a quite older ¹⁴C age of **3,270 ± 50 BP** was reported by **Rivera and Mariño (2004)** from a
880 504 similar deposit at the base of the pumice lapilli fall deposit.

891 505 An isopach map reconstructed from 52 thickness measurements (Fig. 11a) allowed
892 506 plotting thickness (T) versus the square root of the isopach area (A^{0.5}) (Fig. 11b). The
893 507 resulting diagram reveals a regular thinning that fits a single exponential segment (dashed line
894 508 in Fig. 11b). Using the **Pyle (1989)** model, which is based on the exponential decay

901
902
903 509 hypothesis, the bulk tephra volume is 0.007 km³. The [Fierstein and Nathenson \(1992\)](#) method
904
905 510 yielded similar results. By averaging the diameter of the five largest clasts at each outcrop
906
907 511 over the unit's distribution and plotting the lithic isopleths, we estimate the eruption's plume
908
909 512 characteristics using [Carey and Sparks' \(1986\)](#) model. Based on this approach, we estimate a
910
911 513 column height of 11-12 km above sea level. Given that we are considering neither proximal
912
913 514 PDC deposits nor distal fine ash fall deposits, our estimated bulk volume should be
914
915 515 considered as a minimum. Based on this assumption, and the estimated column height, this
916
917 516 event is classified as a small VEI 3 eruption.

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919 517
920 518 ***Pyroclastic-flow deposits.*** At the northeast foot of Yucamane (Pampa Cambaya, 6 km from
921
922 519 the summit), a 5-7 m-thick pyroclastic-flow deposit crops out ([Figs. 10, 11](#)), which covers an
923
924 520 area of 4-5 km² and has a bulk volume of about 0.009 km³. A similar, though thinner (<1-2
925
926 521 m) deposit occurs on the southeast flank of Yucamane. These deposits are composed of three
927
928 522 different subunits that overlie the previously described pumice lapilli fall deposit. The lower
929
930 523 layer has a red-yellow color and is composed of centimeter size, slightly altered pumice (15-
931
932 524 20 vol.%) and lithics (20-25 vol.%) in a friable, fine ash matrix (50-55 vol.%). The middle
933
934 525 layer is grey and composed of large **pumices** up to 50 cm in diameter. The uppermost layer is
935
936 526 ash-rich with disseminated **pumices** up to 20-30 cm in diameter. Pumice bombs with light
937
938 527 grey (63.0-64.3 wt.% SiO₂) and dark grey (61.5 wt.% SiO₂) bands are present in all of these
939
940 528 layers.

941
942 529 Charcoal from the base of this pyroclastic-flow deposit yielded a ¹⁴C age of **2,990 ± 35**
943
944 530 BP (sample YU-13-06A, [Table 3](#)). Comparison between the calibrated ages obtained from
945
946 531 this sample and that obtained at the base of the pumice lapilli fall deposit suggests that these
947
948 532 deposits probably correspond to two different eruptive events.

949 533 950 534 **5.8.5. Potential historical activity?**

951
952 535 Historical reports compiled by [Siebert et al. \(2010\)](#) suggest that Yucamane
953
954 536 experienced repeated eruptions in 1780, 1787, 1802, **1862**, and 1902 CE. [Samaniego et al.](#)
955
956 537 ([2015](#)), however, demonstrate that the 1780-87 and 1802 CE eruptions correspond to the
957
958 538 neighboring Tutupaca volcano, which experienced a sector collapse and large explosive event
959
960 539 that was radiocarbon dated at 218 ± 14 BP. The historical chronicles of [Zamacola \(1888\)](#) and
961
962 540 [Valdivia \(1847\)](#) corroborate that Tutupaca erupted between 1780 and 1802 CE. We found no
963
964 541 chronological or historical data supporting a possible eruption at Yucamane in 1862 and 1902
965
966 542 CE and suggest removing these dates from the volcano's eruptive chronology. Currently,

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962
963 543 Yucamane only has low-intensity, but pervasive fumarolic activity in the summit crater. The
964
965 544 only other geothermal activity in the region is at Calientes hot springs, located 7.5 km
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967 545 northeast of Yucamane.
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969 546

970 547 **6. Main petrological characteristics**

971 548 **6.1. Petrography**

972
973 549 Calientes lavas are porphyritic andesites (~40 % of the dataset) and dacites (~60 %)
974
975 550 with a mineral assemblage of plagioclase, amphibole, biotite, orthopyroxene, clinopyroxene,
976
977 551 and magnetite in an intersertal or intergranular groundmass. Plagioclase (<7 mm) is the most
978
979 552 abundant mineral, followed by amphibole (<2 mm), and pyroxene (<1 mm). Biotite (<1 mm)
980
981 553 is also present in dacitic samples from Calientes III and IV stages. Phenocrysts compose
982
983 554 about 15-20 vol.% of the rocks. Agglomerates of orthopyroxene, clinopyroxene, plagioclase,
984
985 555 and Fe-Ti oxides are also present.

986
987 556 Yucamane lavas are basaltic-andesites (~10 % of the dataset), andesites (~30 %), and
988
989 557 dacites (~60 %), with porphyritic textures and intersertal or intergranular groundmasses.
990
991 558 Basaltic-andesites are only present in the Yucamane III stage and have a phenocryst
992
993 559 assemblage of plagioclase (<2 mm), clinopyroxene (<1.5 mm), orthopyroxene (<600 μm),
994
995 560 amphibole (<500 μm), and magnetite (<200 μm), with rare olivine (<300 μm). Agglomerates
996
997 561 of plagioclase, clinopyroxene, amphibole, and magnetite are present in some samples.
998
999 562 Andesite and dacite samples have porphyritic textures with an intergranular, intersertal, or
1000
1001 563 glassy groundmass, and have a mineral assemblage of plagioclase (<2 mm), amphibole (<3
1002
1003 564 mm), biotite (<3 mm), clinopyroxene (<600 μm), and magnetite (<300 μm). Olivine (<300
1004
1005 565 μm) and orthopyroxene (<1.0 mm) are present in some andesite samples.
1006
1007 566

1002 567 **6.2. Main geochemical characteristics**

1003
1004 568 Calientes and Yucamane samples define a single high-K magmatic trend, from
1005
1006 569 andesites to dacites (60.1-67.7 wt.% SiO_2) for Calientes and from basaltic-andesites to dacites
1007
1008 570 (53.4-66.9 wt.% SiO_2 , [Table 4](#)) for Yucamane. In general, major oxides (except Na_2O and
1009
1010 571 K_2O) are negatively correlated with silica content. As is common in most arc magma series,
1011
1012 572 the light-ion lithophile elements (LILE, e.g. K, Rb, Th) and the light rare earth elements
1013
1014 573 (LREE, e.g. La, Ce, Nd) show positive correlations with silica content ([Fig. 12](#)), although the
1015
1016 574 LREE have scattered trends. In contrast, Sr, Y, the medium rare earth elements (MREE, e.g.
1017
1018 575 Sm, Eu, Gd), the heavy rare earth elements (HREE, e.g. Dy, Er, Yb) and the transition metals

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1022
1023 576 (e.g. Cr, Ni, V) are all reversely correlated with silica. Some **high-field-strength** elements
1024
1025 577 (HFSE, e.g. Zr) are also reversely correlated with silica.

1026 578 The variation diagrams clearly show a single magmatic trend for samples from both
1027
1028 579 Calientes and Yucamane. Slight variations, however, are present in the major and trace
1029
1030 580 elements' behavior through time. For instance, Calientes volcano erupted dominantly
1031
1032 581 andesitic and dacitic magmas with rare eruptions involving silica-rich magmas such as the
1033 582 Callazas ignimbrite (Calientes II stage). In contrast, Yucamane has a different pattern that
1034
1035 583 includes a progressive decrease in silica content through time, with Yucamane's Holocene
1036 584 eruption products **being** among the most mafic examples from the entire Yucamane-Calientes
1037
1038 585 magmatic series.

1039 586 1040 1041 587 **7. Discussion**

1042 588 **7.1. Evolution of two adjacent edifices**

1044 589 On the basis of the stratigraphic, geochronological and geochemical data, we propose
1045
1046 590 that Yucamane-Calientes represents a single compound volcano with two, adjacent and
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1048 591 partially contemporaneous eruption centers (**Fig. 13**). Calientes developed from ~500 ka to
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1050 592 the late Holocene (~3 ka) and was characterized by dome-forming activity with a large
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1052 593 explosive eruption at ~160-190 ka. The large volume (8-12 km³) and distribution of the
1053
1054 594 ignimbrite deposits, and the presence of a proximal lag breccia facies in the Río Callazas
1055
1056 595 valley point to a source related with the YCCV. Such an interpretation is consistent with the
1057
1058 596 petrology, which shows that the dacitic pumices of the Callazas ignimbrite form the high-
1059
1060 597 silica end-member of the Yucamane-Calientes magmatic series. Due to the significant volume
1061
1062 598 of these deposits, we suggest this eruption formed a 3-5 km-wide caldera, which is likely
1063
1064 599 concealed beneath Calientes and Yucamane. The bulk volume of the **ignimbrite** deposits
1065
1066 600 suggests that this eruption is at the limit between VEI 5 and 6. We suggest, however, that
1067
1068 601 because the volume of the potential corresponding tephra-fall deposit is not included that this
1069
1070 602 volume should be considered a minimum. As such, we suggest that this eruption was likely a
1071
1072 603 VEI of 6. As shown in **Fig. 13**, following the Callazas ignimbrite, the main cone-forming
1073
1074 604 stage of Calientes occurred between 130 and 100 ka (Calientes III stage). After a long time-
1075
1076 605 gap, volcanic activity resumed in the Holocene (Calientes IV stage).

1071 606 Yucamane was constructed on top of the remnants of Calientes' older units (Calientes
1072
1073 607 III stage) and developed since at least ~36 ka (i.e. the age of the Yucamane blast deposits).
1074
1075 608 This age is a minimum because we have no age determination for the older Yucamane lava
1076
1077 609 flows (Yucamane I stage). This edifice was very active between ~40 ka and the Holocene

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1082
1083 610 (Yucamane II and III stages). During at least the late Holocene, both eruptive centers were
1084
1085 611 active. Both edifices, however, produced distinct magmatic products during the Holocene:
1086 612 dominantly dacites for Calientes' recent domes, and basaltic-andesites to andesites for
1087
1088 613 Yucamane, suggesting a complex shallow magmatic plumbing system. Other examples for
1089
1090 614 adjacent and contemporaneously eruptive volcanoes in the Andes include the Mojanda-Fuya
1091 615 Fuya volcanic complex (Robin et al., 2009), which shows contrasting eruptive dynamics and
1092
1093 616 magma chemistry during their Late Pleistocene history. Another example is the twin-peaked
1094 617 Ilinizas volcanoes in the Ecuadorian segment of the Northern Volcanic Zone (Hidalgo et al.,
1095
1096 618 2007). In the Peruvian volcanic arc, the Ampato-Sabancaya compound volcano (Samaniego et
1097
1098 619 al., 2016) also has a progressive shift of the eruptive activity from Ampato to Sabancaya with
1099 620 a transitional period at the Pleistocene-Holocene transition during which both volcanoes were
1100
1101 621 active.

1102 622

1103 623 **7.2. Petrogenetic processes at YCCV**

1104 624 The geochemical study of the major and trace elements shows that the magmatic
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1106 625 evolution of the YCCV is controlled by processes that include fractional crystallization and
1107 626 assimilation of crustal materials. This point is clearly shown by the well-defined trends for
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1109 627 most major and trace elements as well as the homogeneous spider diagrams for samples from
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1111 628 both Yucamane and Calientes edifices (Fig. 14a). To test these hypotheses, a diagram based
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1113 629 on the geochemical behavior of one of the most incompatible elements (e.g. Rb) *versus* a
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1115 630 compatible element (e.g. Ni) is commonly used to discriminate fractional crystallization (and
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1117 631 other differentiation processes) from source-related partial melting (Janoušek et al., 2015). In
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1119 632 a log (compatible element) *versus* log (incompatible element) plot, differentiated liquids
1120 633 produced by partial melting show a sub-horizontal trend, whereas fractional crystallization
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1122 634 would rise to a sub-vertical trend. Plotting log (Ni) *versus* log (Rb) yields clearly defined sub-
1123 635 vertical trends (Fig. 14b), suggesting that fractional crystallization is the key process driving
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1125 636 magma differentiation at YCCV. Our mineralogical and geochemical data from Yucamane-
1126 637 Calientes highlights the prominent role played by fractional crystallization processes as
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1128 638 expressed by: (1) the presence of zoned plagioclase and clinopyroxene phenocrysts; (2) the
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1130 639 marked correlation between highly incompatible elements; and (3) the depletion of
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1132 640 compatible elements along differentiation trends in the magma. For instance, a decrease in Ni
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1134 641 and Cr with increasing silica suggests olivine and/or clinopyroxene fractionation, whereas a
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1136 642 decrease in Sr and Eu concentrations suggests plagioclase crystallization. The depletion in
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1138 643 MREE and HREE, which is typical of intermediate and silica-rich Andean magmas further

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1143 644 strongly suggests a key role of amphibole fractionation in the arc crust (Davidson et al.,
1144 645 2007).

1146 646 In their regional isotopic study of CVZ magmatism, Mamani et al. (2010) published
1147 646 some isotopic data for Yucamane samples. These data reveal high $^{87}\text{Sr}/^{86}\text{Sr}$ (0.7064-0.7068)
1148 647 and low $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (0.51226-0.51233). They further report Pb isotope ratios
1149 648 and low $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (0.51226-0.51233). They further report Pb isotope ratios
1150 648 ($^{206}\text{Pb}/^{204}\text{Pb}$ 18.066-18.220; $^{207}\text{Pb}/^{204}\text{Pb}$ 15.584-15.643, and $^{208}\text{Pb}/^{204}\text{Pb}$ 38.474-38.685)
1151 649 similar to those of the metamorphic basement (Barreiro and Clark, 1984). In general, regional
1152 650 studies highlight the link between Pb isotope compositions of the upper crust and those of the
1153 651 erupted CVZ magmas (James, 1982; Harmon et al., 1984; Aitchison et al., 1995). Such Pb
1154 652 isotope data further supports the inference from Sr and Nd isotopic systems that CVZ magmas
1155 653 assimilated significant amounts of the regional metamorphic basement during their evolution.
1156 654

1159 654 We infer that the Yucamane-Calientes magmas evolved by AFC processes which
1160 655 include significant fractionation of amphibole coupled with assimilation of upper crustal
1161 656 material, following the model for Central Andean magmatism proposed by several authors
1162 657 (e.g., Hildreth and Moorbath, 1988; Davidson et al., 1991; Delacour et al., 2007; Mamani et
1163 658 al., 2010; Godoy et al., 2014; Samaniego et al., 2016; Blum-Oeste and Wörner, 2016; Rivera
1164 659 et al., 2017). The depth of contamination, however, is still debated. Some suggest
1165 660 contamination in the lowermost crust through MASH-type processes (Hildreth and Moorbath,
1166 661 1988; Davidson et al., 1990; Delacour et al., 2007), whereas others propose that
1167 662 contamination occurred during ascent and storage of the magma through the upper crust
1168 663 (James, 1984; Davidson et al., 1990; Gerbe and Thouret, 2004; Rivera et al., 2017). The
1169 664 models are not mutually exclusive, but a detailed and quantitative assessment of such
1170 665 petrogenetic processes is beyond the scope of this work.
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1181 668 **7.3. Late Holocene eruptive activity and related hazards**

1183 669 The last eruptive phase of Calientes occurred during the Holocene and was
1184 670 characterized by dome-growth and subsequent collapse. Yucamane also experienced at least
1185 671 4-5 explosive events during late Holocene times. These eruptions had a local impact and were
1186 672 characterized by tephra-fall deposits that were usually dispersed to the ESE and frequent
1187 673 pyroclastic density currents that swept down the cone, reaching 4-5 km from the summit.
1188 674 Based on geologic and tephrochronologic data, the most probable eruptive scenario at
1189 675 Yucamane would be low-to-moderate magnitude (VEI 1-2) vulcanian activity accompanied
1190 676 by tephra emissions, similar to recent eruptions at Ubinas (2006-2009, 2013-2015 CE) and
1191 677 Sabancaya (1990-1998, 2015-2018 CE). This scenario could evolve to higher magnitude

1201
1202
1203 678 events including the emplacement of more voluminous tephra-fall deposits and triggering of
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1205 679 pyroclastic density currents around the cone, as occurred during the 3,000 BP, **sub-Plinian**
1206 680 (VEI 3) eruption of Yucamane. The large magnitude and **explosive** dome-forming events that
1207
1208 681 impacted the old Yucamane and Calientes edifices were also considered in the volcanic
1209
1210 682 hazard map for the YCCV (Rivera et al., 2018). Secondary lahars may follow any eruptive
1211 683 phases because of rainfall or melting of the snow/ice that usually caps Yucamane's summit
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1213 684 during the local winter (December-July).
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1215 685

1216 686 **8. Conclusions**

1217
1218 687 The YCCV comprises two successive edifices. Calientes was constructed in four main
1219 688 stages. The older rocks of Calientes are andesitic lava flows at the base of the volcano, dated
1220
1221 689 at 450-500 ka. The Callazas ignimbrite (Calientes II stage) was then emplaced (~160-190 ka),
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1223 690 followed by the main cone-building stage (Calientes III), dated at 130-100 ka. Finally, the
1224 691 Holocene Calientes domes were emplaced and represent the last eruptive products of this
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1226 692 edifice. Yucamane was built in three eruptive stages. The Yucamane I stage consists of a
1227 693 sequence of andesitic lava flows exposed at the base of the volcano with an age older than 40
1228
1229 694 ka. The Yucamane II stage (~36-30 ka) comprises a thick sequence of block-and-ash-flow
1230 695 deposits that represents a dome-growth episode predating the younger Yucamane cone
1231
1232 696 (Yucamane III stage) dated at 25-3 ka. During the Holocene, Yucamane experienced at least
1233
1234 697 4-5 explosive eruptions characterized by tephra dispersal and pyroclastic density currents on
1235 698 most flanks of the cone. The last explosive event of Yucamane occurred at 3,000 BP and was
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1237 699 a **sub-Plinian** VEI 3 eruption that emplaced a conspicuous tephra-fall deposit to the east-
1238 700 southeast and a pyroclastic-density-current deposit on the northeast and western flanks.
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1240 701 Samples from Calientes generally have andesite and dacite compositions (60.1-67.7 wt.%
1241
1242 702 SiO₂), while Yucamane's rocks have a slightly larger compositional range from basaltic-
1243 703 andesites to dacites (53.4-66.9 wt.% SiO₂). The rocks have a similar mineral assemblage of
1244
1245 704 plagioclase, amphibole, biotite, ortho- and clino-pyroxene, Fe-Ti oxides, and scarce olivine.
1246 705 Such characteristics suggest that both Calientes and Yucamane belong to a common
1247
1248 706 magmatic system. On the basis of the geologic, **geochronological**, and petrologic data, we
1249
1250 707 consider Yucamane-Calientes as a potentially active volcanic center.
1251 708

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Figures

Fig. 1. (a) Location map of South American volcanic zones: Northern (NVZ), Central (CVZ), Southern (SVZ), and Austral (AVZ) (modified after Stern, 2004). **(b)** Northernmost part of the CVZ in southern Peru (modified after Thouret et al., 2005). The YCCV is located south of the Plio-Quaternary volcanic range of southern Peru, 13 km northeast of the town of Candarave. **(c)** View of the western flank of Yucamane and Calientes from Candarave.

Fig. 2. Geologic map of YCCV showing the locations of dated rock samples.

Fig. 3. Panoramic view of YCCV showing some of the main structures. **(a)** View from the west showing the former Calientes and Yucamane stratocones near Yucamane Chico. **(b)** A recent dome complex between Calientes and Yucamane that was not affected by Pleistocene-Holocene glacial activity. **(c)** Callazas ignimbrite emplaced at ca. 160-190 ka, exposed above the San Lorenzo sector, 8 km west of Calientes' summit.

Fig. 4. (a) Density plot (red continuous curve) of anorthoclase crystals from sample YU-12-78, along with individual $^{40}\text{Ar}/^{39}\text{Ar}$ age distribution (error bars are 2σ). The grey curve is plotted using all analyses. The red curve uses analyses providing the best probability of fit (red dots in the age distribution diagrams). N = number of crystals retained in the age calculation over the number of crystals analyzed. P = probability of fit. **(b)** Inverse isochrones depicting $^{40}\text{Ar}/^{39}\text{Ar}$ results. Uncertainties are $\pm 1\sigma$. Grey ellipses are not included in the inverse isochron calculations.

Fig. 5. Plot of LA-ICP-MS ^{231}Pa - ^{230}Th corrected U-Pb zircon ages according to rank. Vertical black bars represent 2σ analytical uncertainties. The grey horizontal bands are cumulative weighted mean values for the considered population. Both samples come from the Callazas ignimbrite: **(a)** Sample YU-12-78A represents the upper surge deposits and **(b)** YU-13-07 is from the structureless middle unit.

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943 **Fig. 6. (a)** Sequence of blast, debris-avalanche, and block-and-ash-flow deposits exposed on
944 the north-western bank of Quebrada Curancurane, 6 km southwest of Yucamane. **(b)**
945 Sequence of Salado dacitic block-and-ash-flow deposits exposed on the western bank of Río
946 Salado, 7 km southeast of Yucamane. **(c)** Pyroclastic succession in Quebrada Honda, 9 km
947 south of Yucamane.

948
949 **Fig. 7.** Stratigraphic sections of pyroclastic-flow and tephra-fall deposits associated with
950 YCCV. UTM Easting and Northing are given below the section name.

951
952 **Fig. 8. (a)** Scoria-rich pyroclastic-flow deposit cropping out on the western bank of Quebrada
953 Condorcahua ravine, 7 km southwest of the crater of Yucamane, covered by a pumice-rich
954 lahar deposit. **(b)** Lower Halloween and Upper Halloween scoria-rich tephra-fall deposits that
955 crop out in the Hueltajavira sector, 6 km southeast of Yucamane's crater. **(c)** Lower
956 Halloween tephra-fall deposit in the Mal Paso area, 4 km south of the crater. **(d)** Parda scoria-
957 rich tephra-fall deposit cropping out 4.5 km south of the crater.

958
959 **Fig. 9.** Stratigraphic sections of the pyroclastic-flow and tephra-fall deposits associated with
960 YCCV. UTM Easting and Northing are included below the section's name.

961
962 **Fig. 10. (a)** The pumice lapilli-rich tephra-fall deposit dated at $3,085 \pm 35$ BP that crops out at
963 the foot of Yucamane's eastern flank. **(b)** The pumice-rich pyroclastic-flow deposit dated at
964 $2,920 \pm 35$ BP, which crops out at Yucamane's lower northeast flank.

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966 **Fig. 11. (a)** Map showing isopachs for the pumice lapilli-rich tephra-fall deposit dated at
967 $3,085 \pm 35$ BP and area covered by associated ash-and-pumice-rich pyroclastic flows. **(b)** T
968 vs. $A^{0.5}$ diagram, T and A being thickness and surface covered by isopachs respectively.

969
970 **Fig. 12.** Selected major and trace elements for Yucamane-Calientes samples, plotted against
971 silica. **(a)** SiO_2 vs. K_2O classification diagram. A andesites, D dacites, R rhyolites, MK
972 medium potassium, HK high-potassium (after Peccerillo and Taylor, 1976). **(b-h)** Variation
973 diagrams for Al_2O_3 , MgO, Sr, Zr, Rb, $\text{K}_2\text{O}/\text{TiO}_2$, and La, respectively.

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975 **Fig. 13.** Composite lithostratigraphic section showing the geologic and volcanologic
976 evolution of YCCV.

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Fig. 14. (a) Multi-element diagrams normalized to primitive mantle (Sun and McDonough, 1989) showing typical trace element patterns of continental arc magmas in Yucamane-Calientes samples. **(b)** Log (Ni) vs. Log (Rb) diagram for Yucamane-Calientes samples. We observe a large variation of compatible element (Ni) compared with the variation of an incompatible element (Rb). This trend is mostly explained by fractional crystallization process. FC fractional crystallization; PM partial melting.

Table 1. K-Ar ages for rocks from the Yucamane-Calientes compound volcano.

Table 2. $^{40}\text{Ar}/^{39}\text{Ar}$ ages for rocks from the Yucamane-Calientes compound volcano. **The ages considered in the text are the weighted mean ages (in bold).**

Table 3. ^{14}C data for YCCV measured at the Center for Isotope Research, Groningen University (The Netherlands).

Table 4. Selected geochemical analyses representative of the main volcanic units of YCCV.

Supplementary material 1. Analytical methods.

Supplementary material 2. $^{40}\text{Ar}/^{39}\text{Ar}$ data from laser-fusion experiments on plagioclase crystals relative to 1.1891 Ma ACs-2 flux standard.

Supplementary material 3. In situ U-Pb zircon data measured by LA-ICP-MS on YU-12-78A and YU-13-07 samples.

Highlights

-Yucamane-Calientes is a compound volcano composed of two edifices of middle Pleistocene to the Holocene

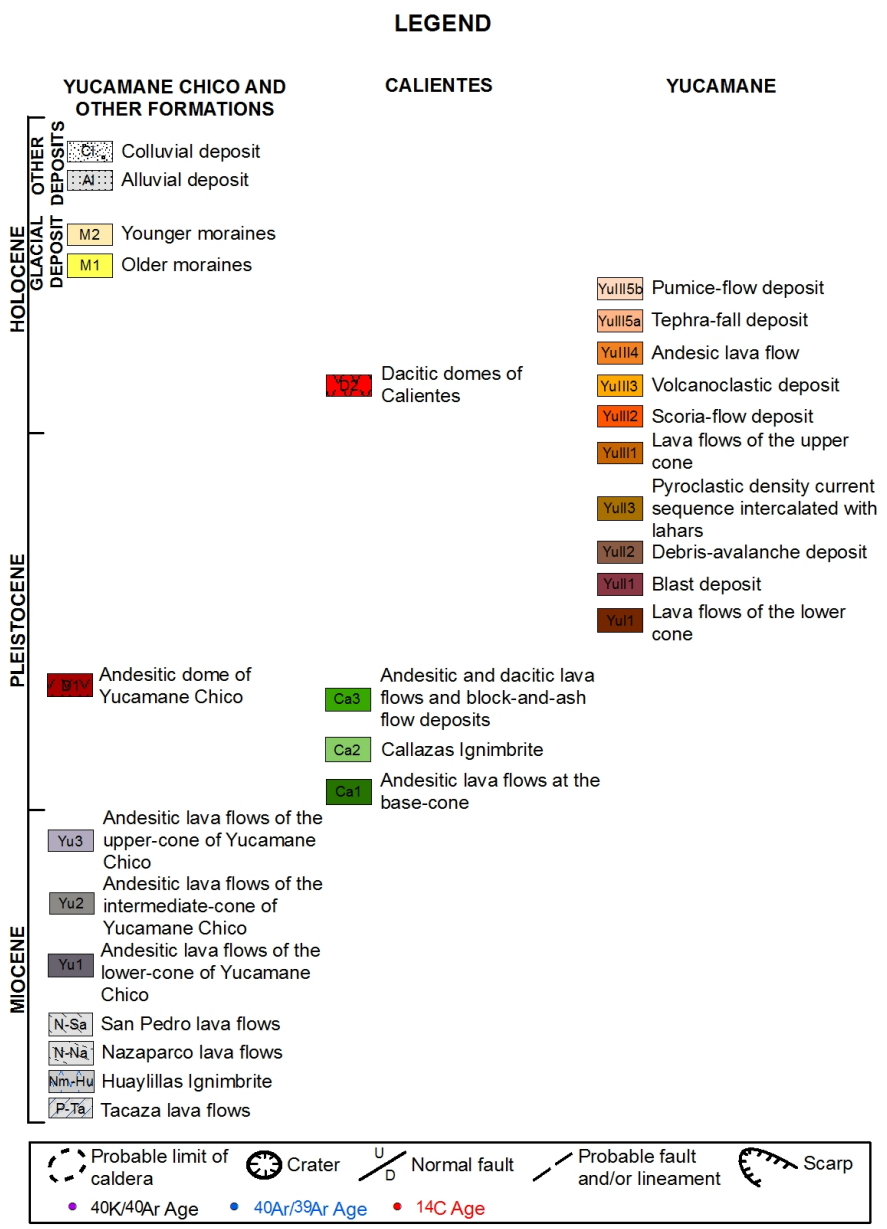
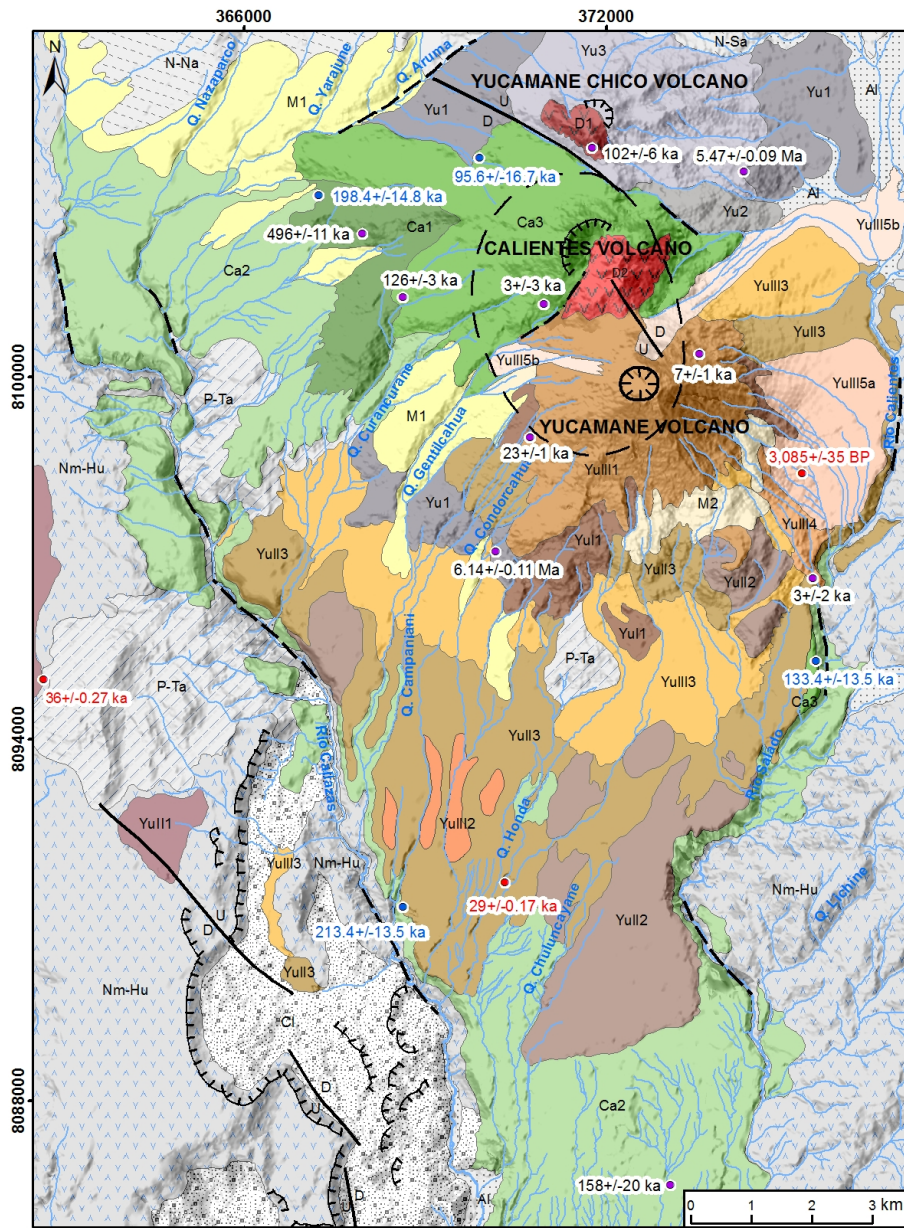
- Calientes has been constructed in four stages since ~500 ka and Holocene

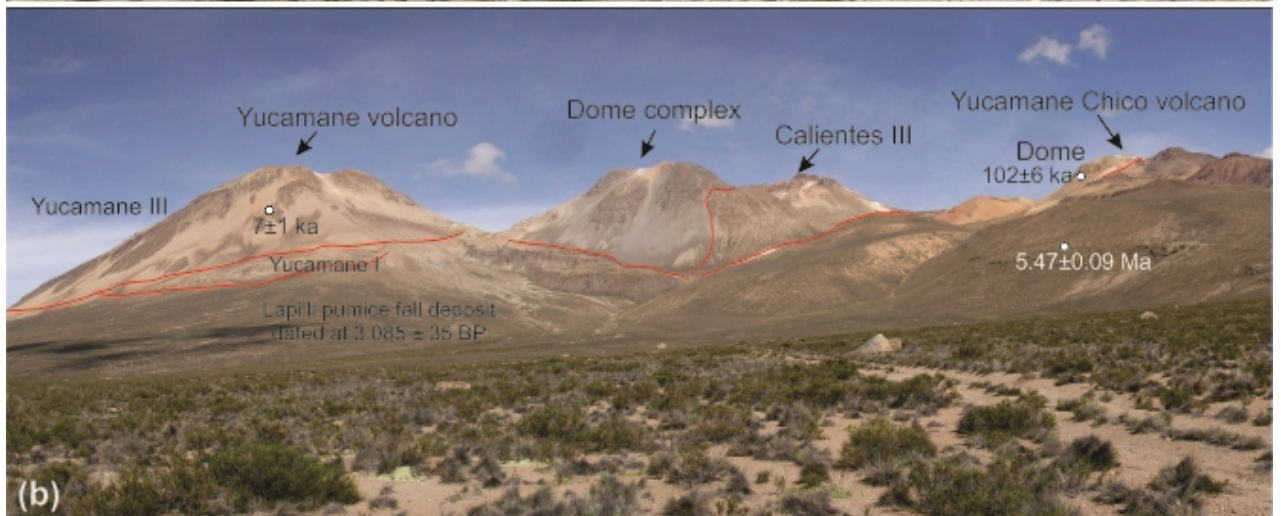
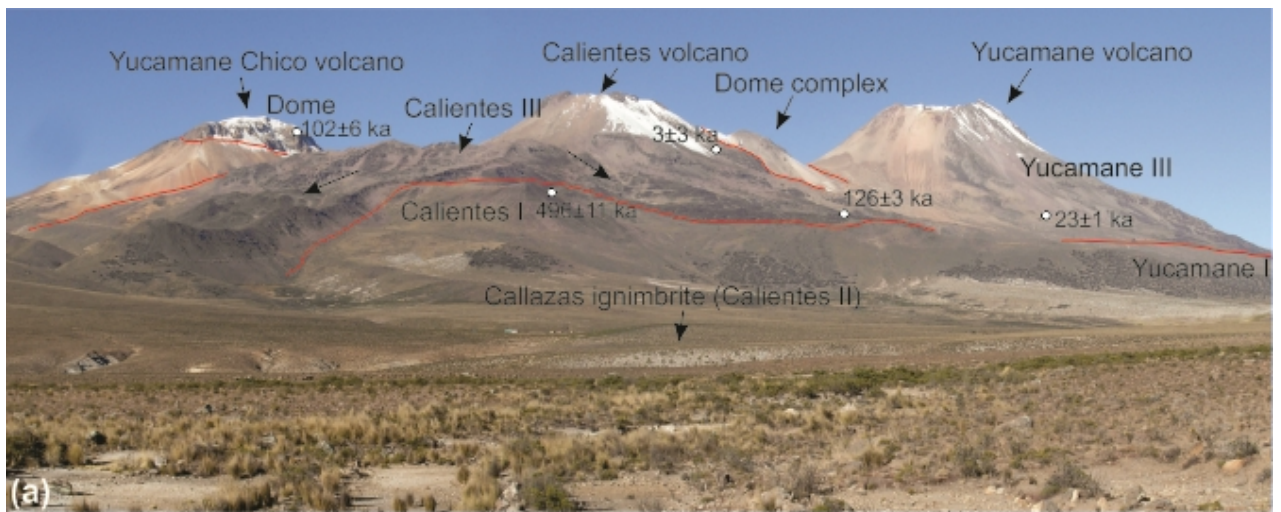
- Yucamane has been constructed in three stages between ~40 ka and Holocene

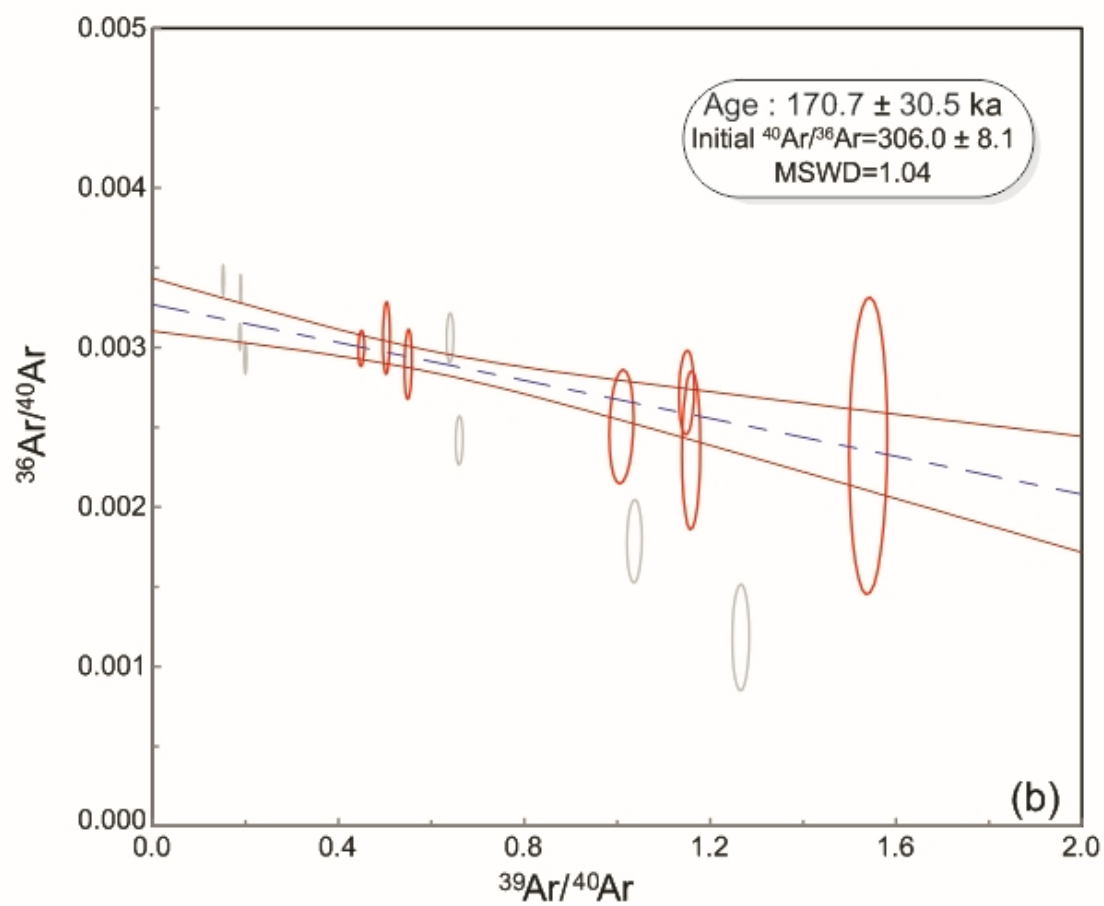
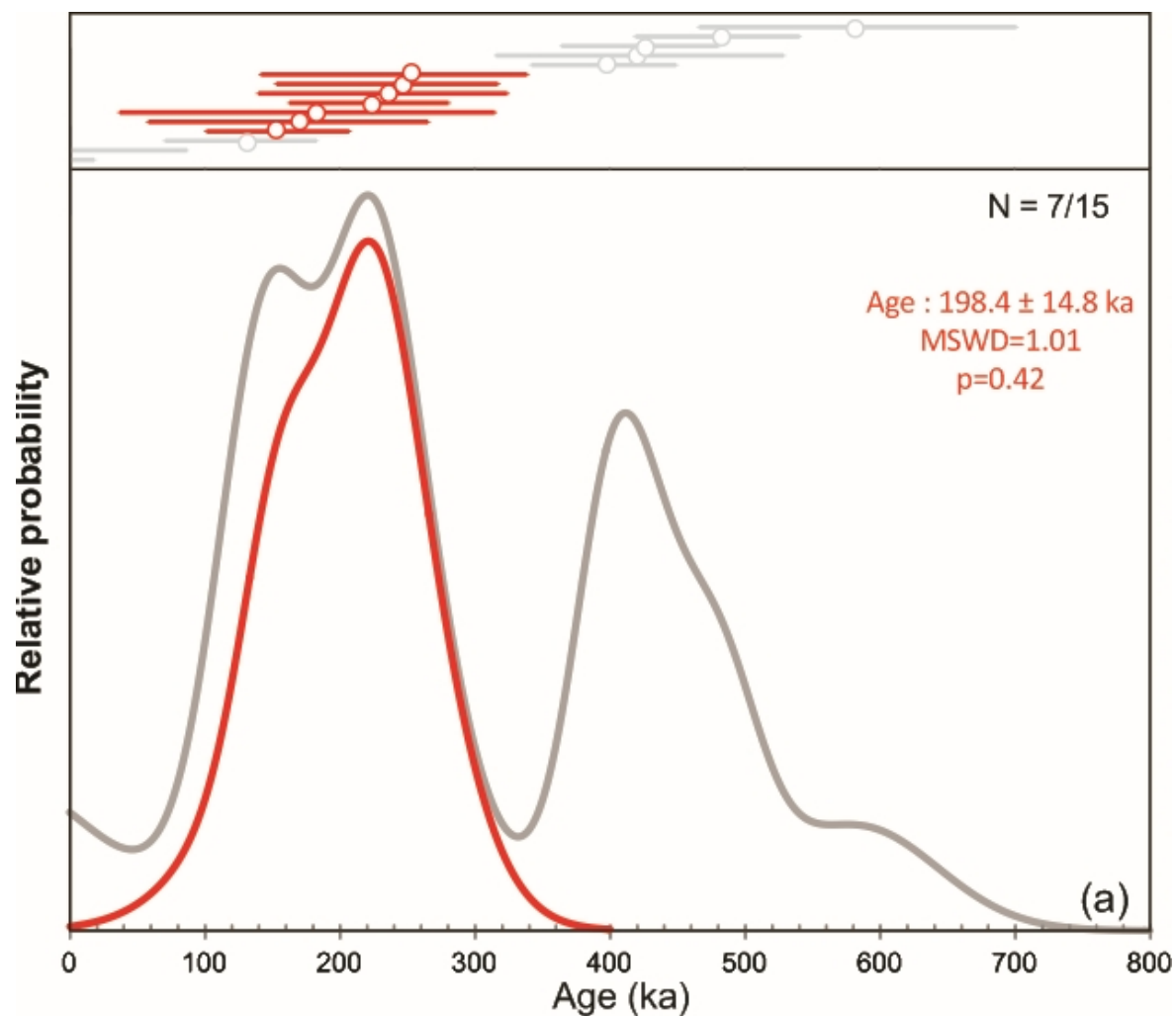
- Samples from both volcanoes are high-K calc-alkaline andesites and dacites

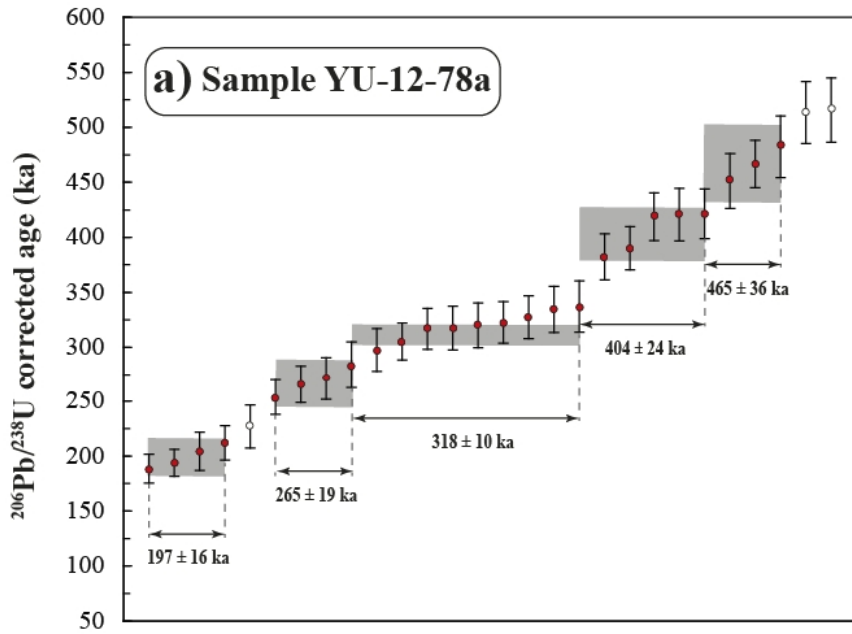
-During the Holocene, Yucamane experienced repetitive vulcanian to sub-plinian eruptive activity that emplaced tephra-fall and pyroclastic-density-current deposits

- Yucamane-Calientes should be considered as a potentially threatening volcano

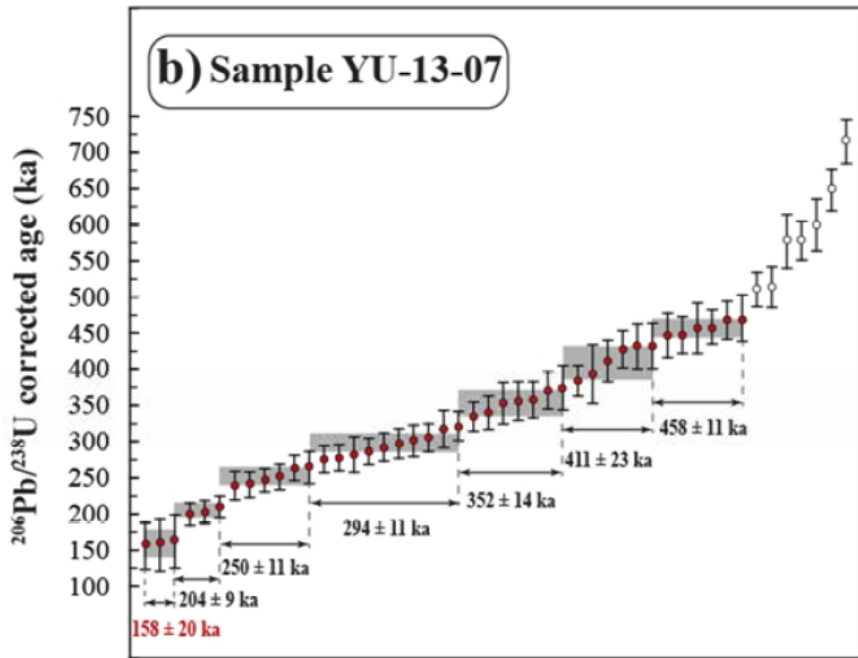




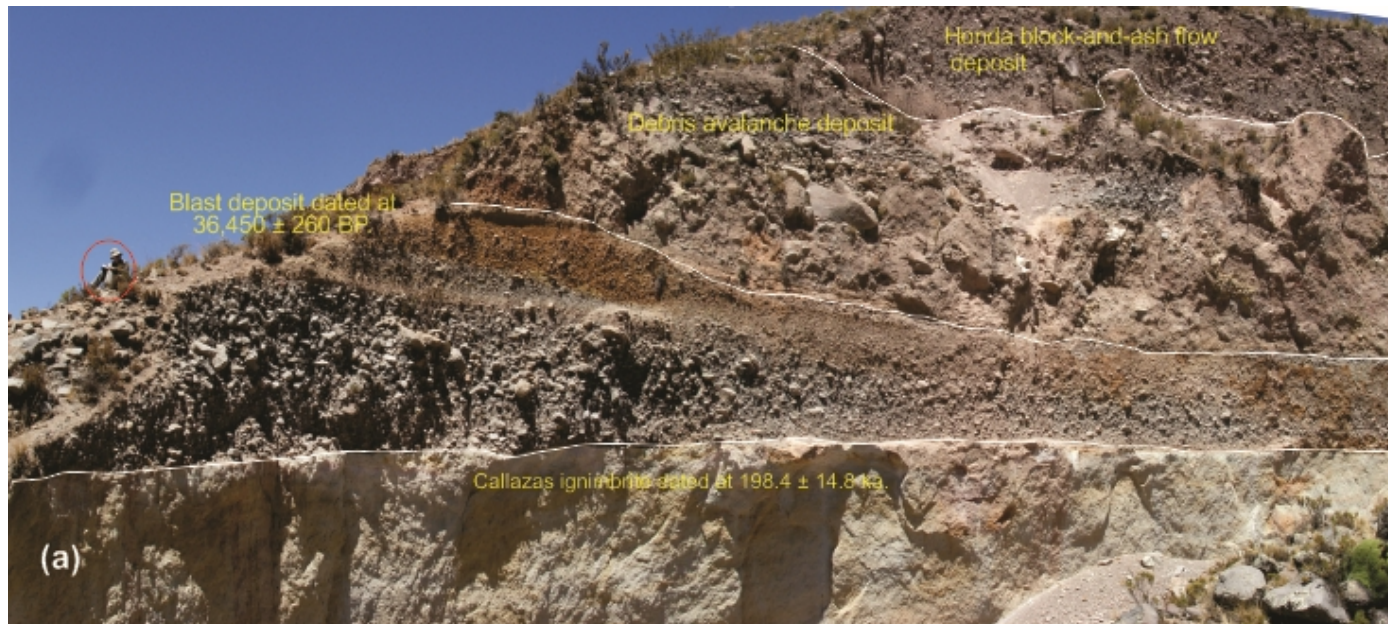




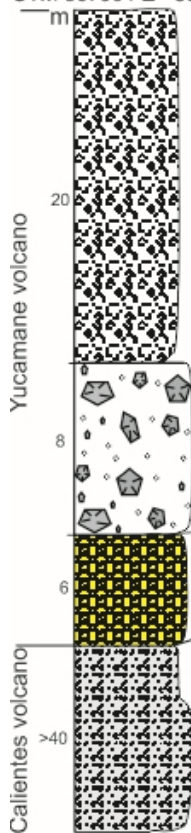
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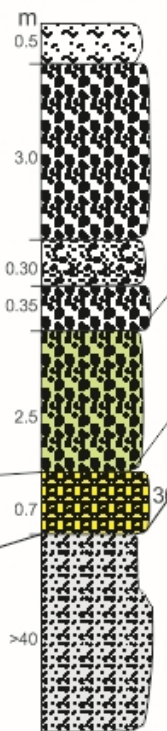
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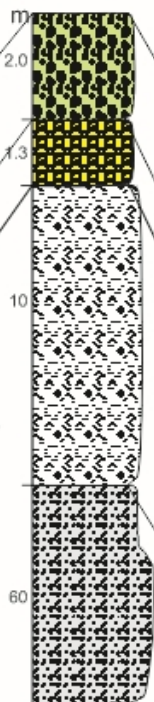
Quebrada Curancurane
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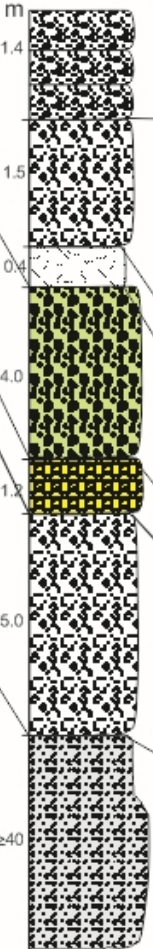
Quebrada Gentilcahua
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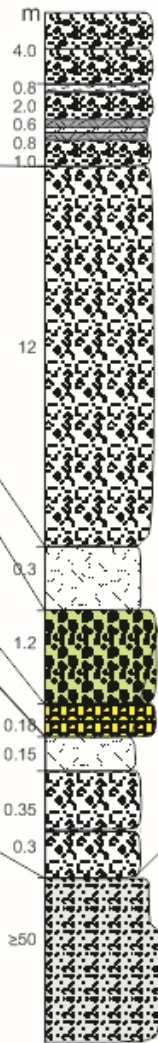
Yucamane town
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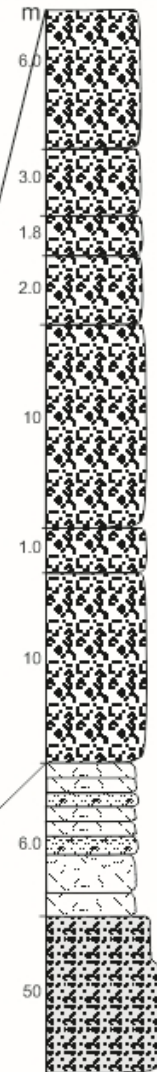
Quebrada Campanani
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Quebrada Honda
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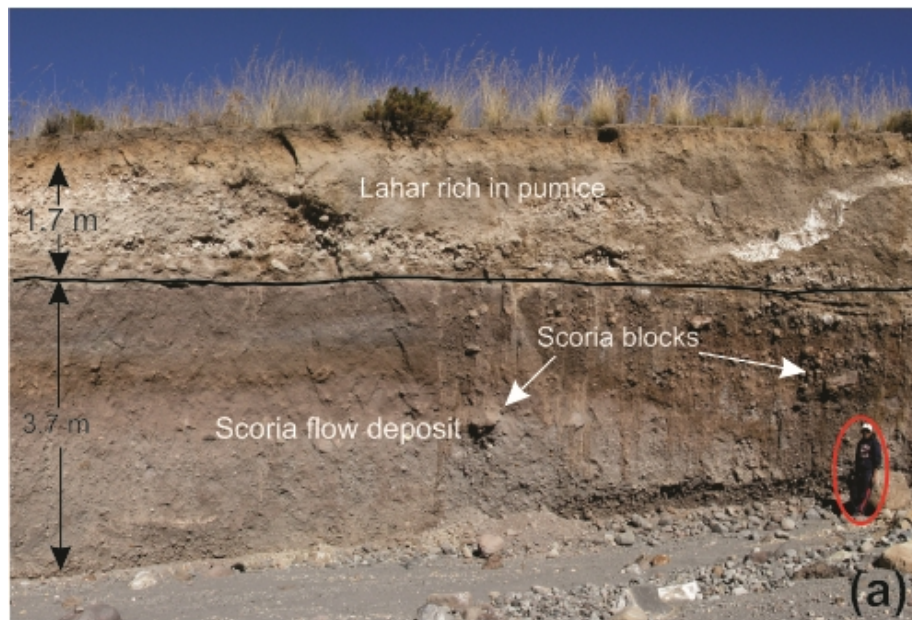


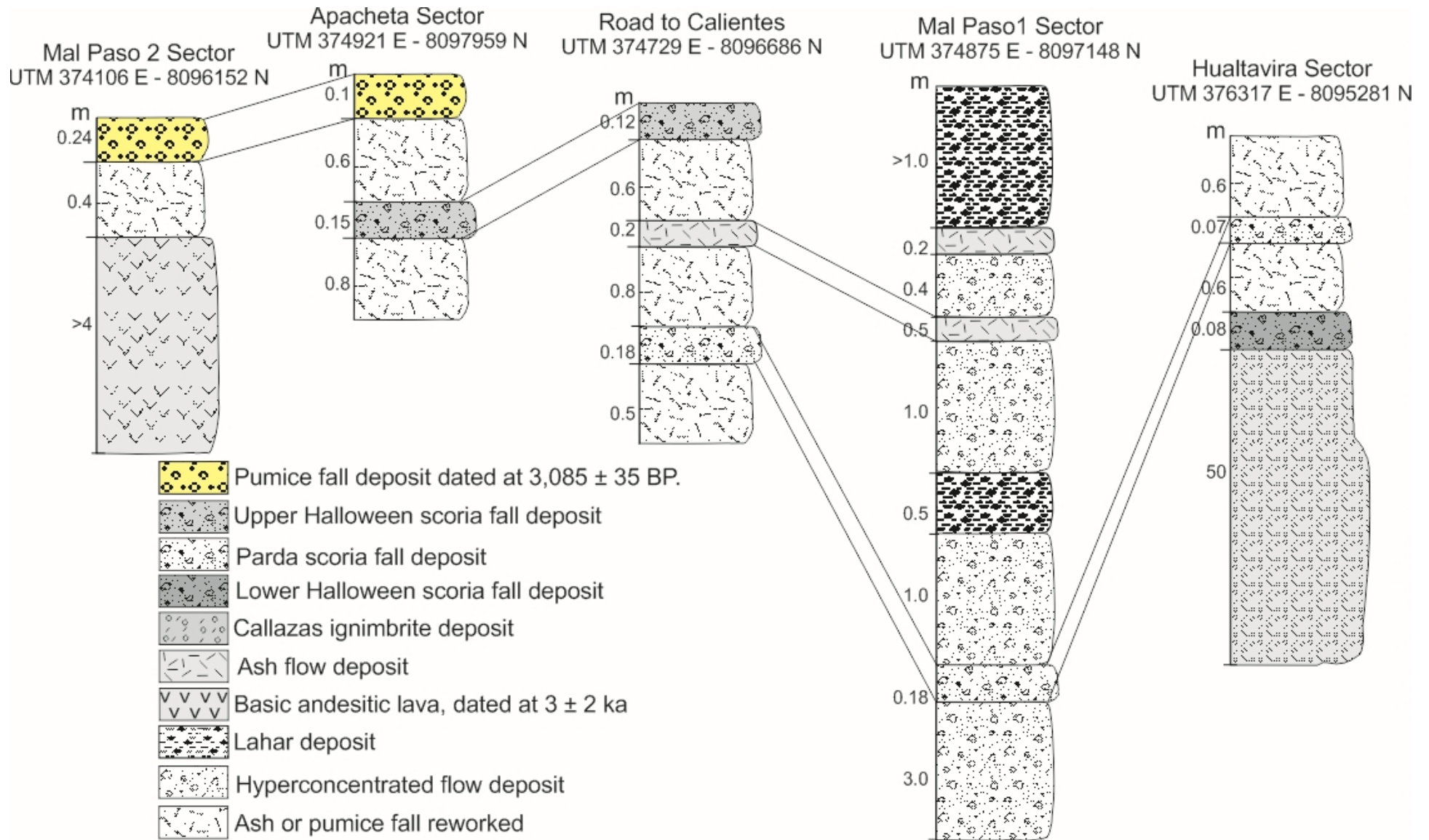
Salado River
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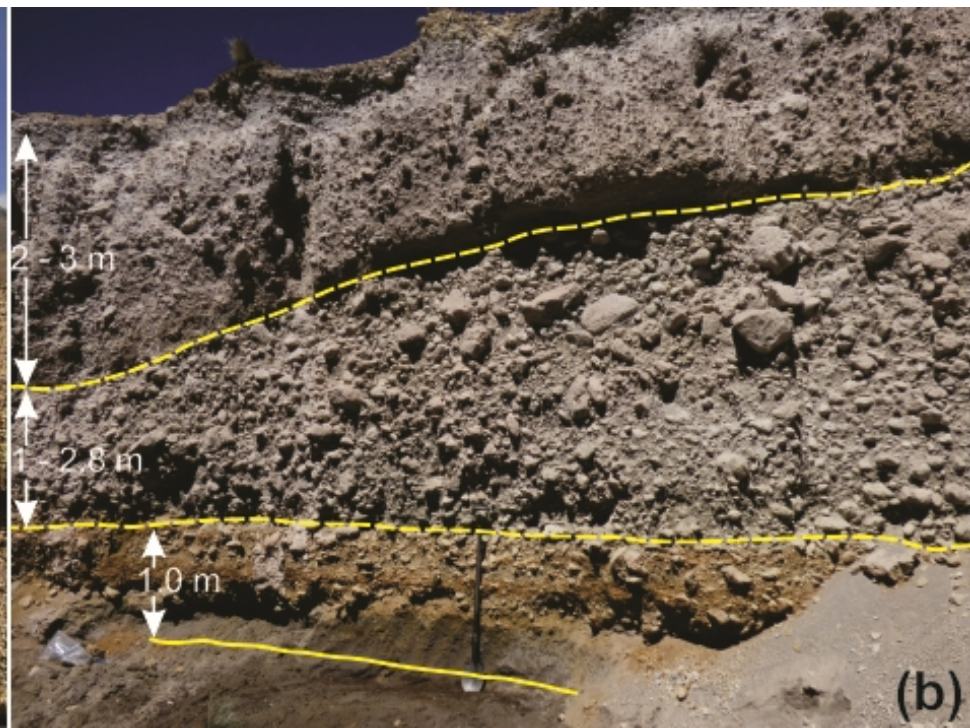
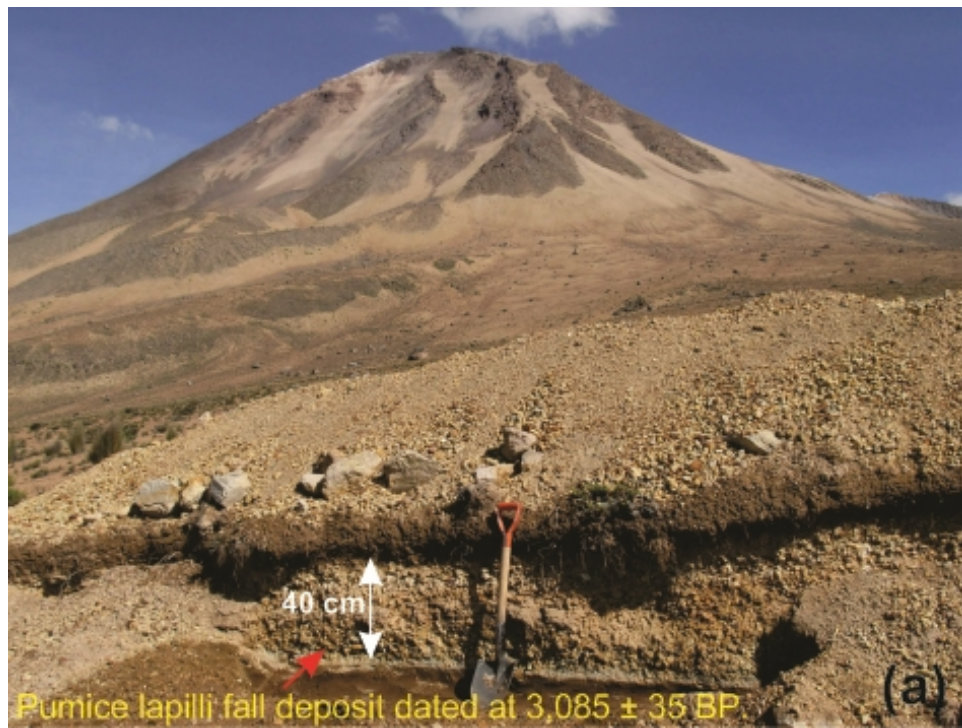


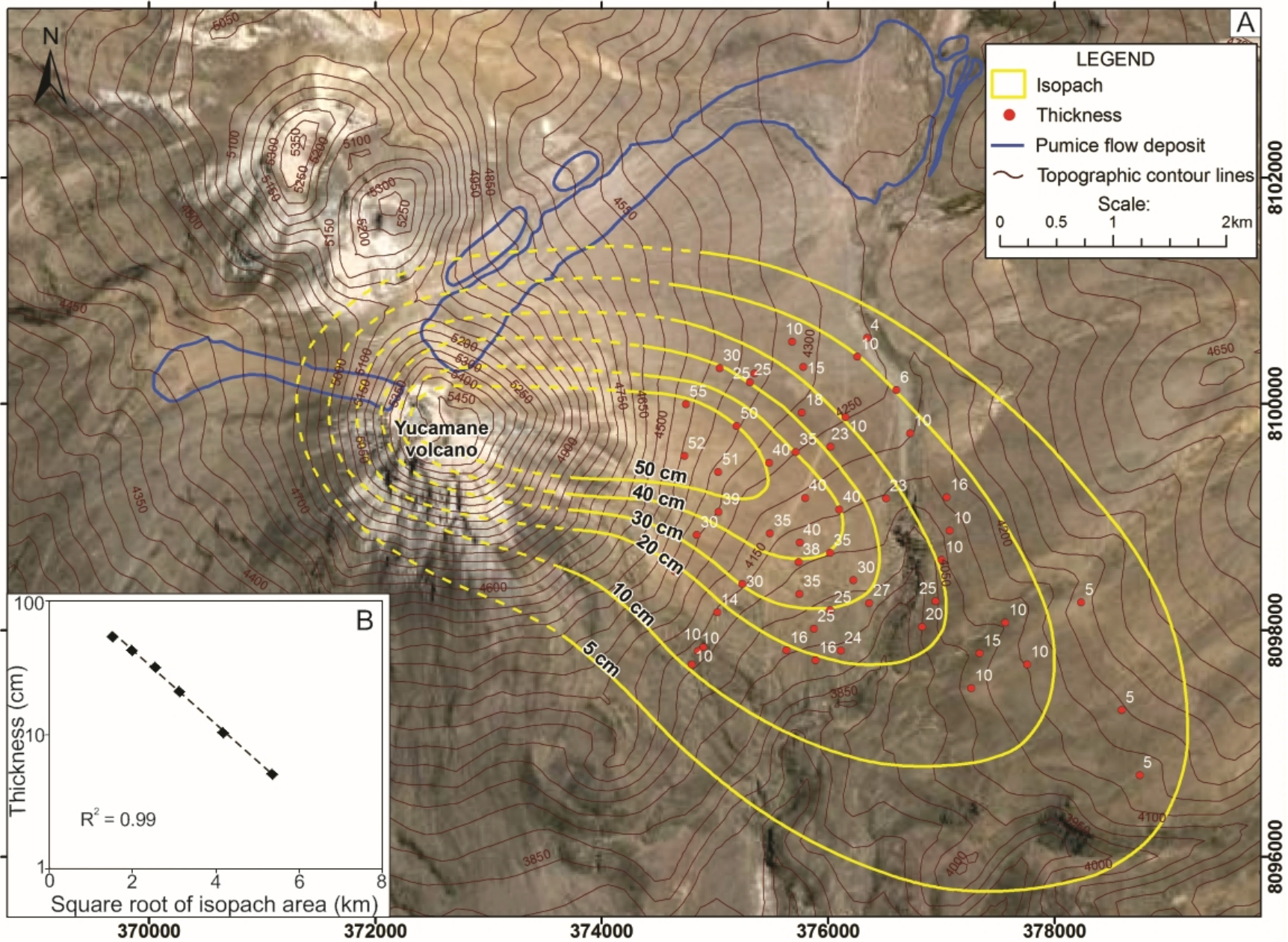
Legend

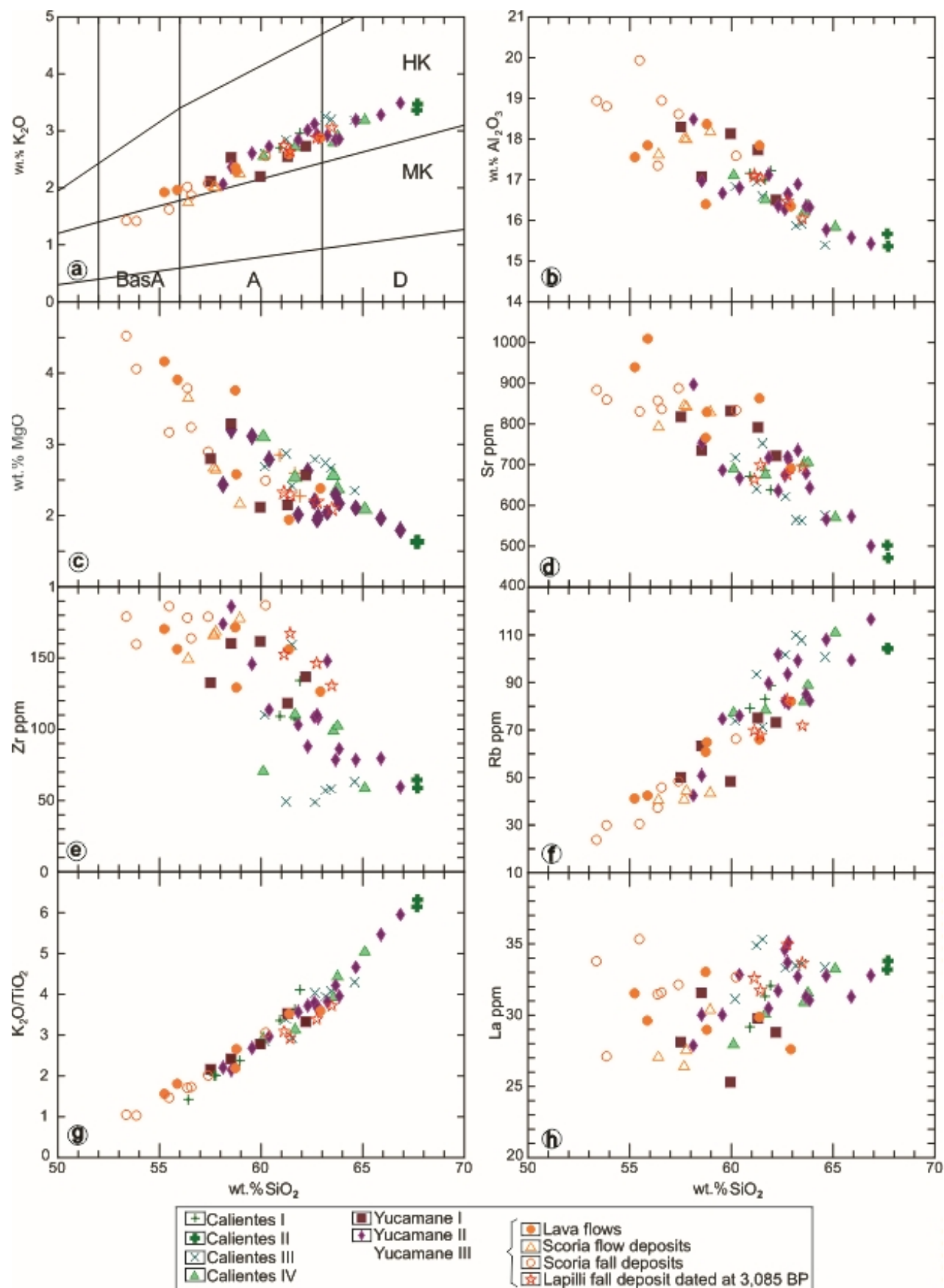
- Lahar
- Pumice flow deposit
- Ash fall deposit
- Scoria fall deposit
- Scoria flow deposit
- Ash flow deposit
- Campanani block-and-ash flow deposit
- Debris avalanche deposit
- Blast deposit dated at 36,450 ± 270 BP.
- Block-and-ash flow deposit
- Callazas ignimbrite (Calientes II unit)

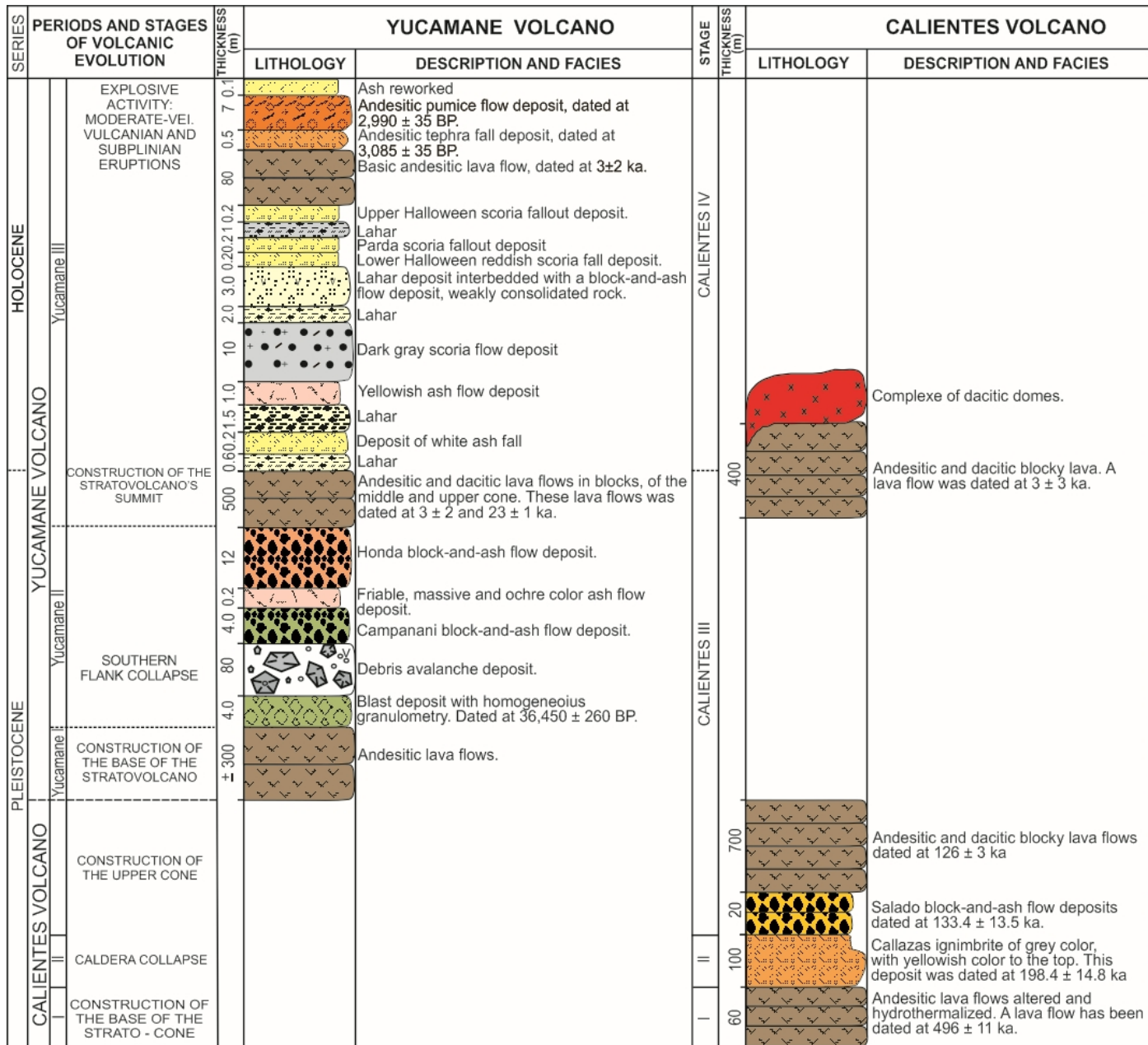


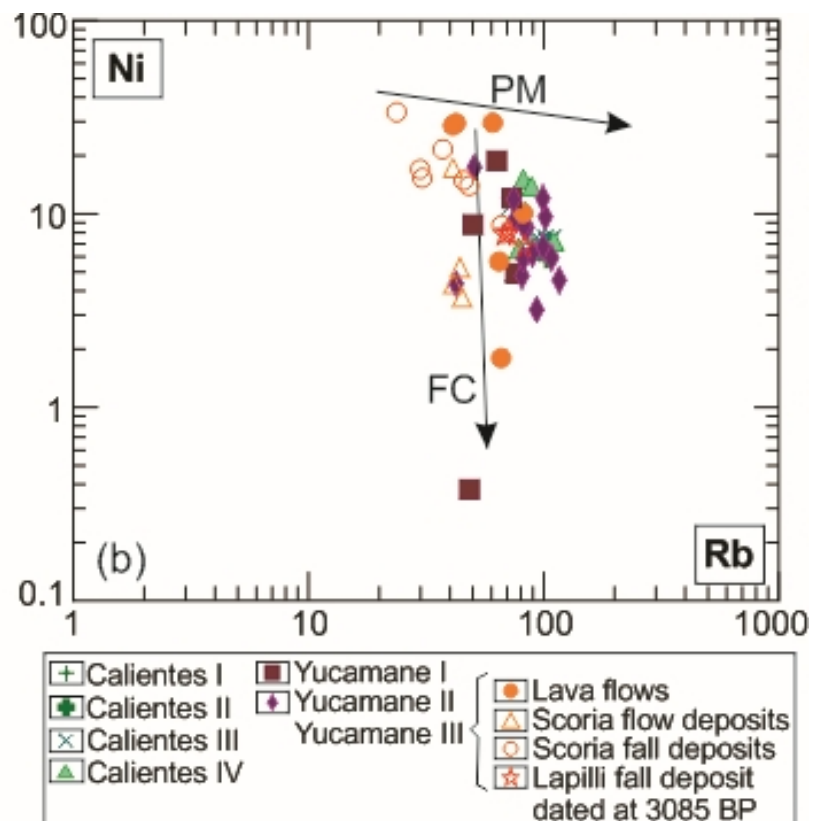
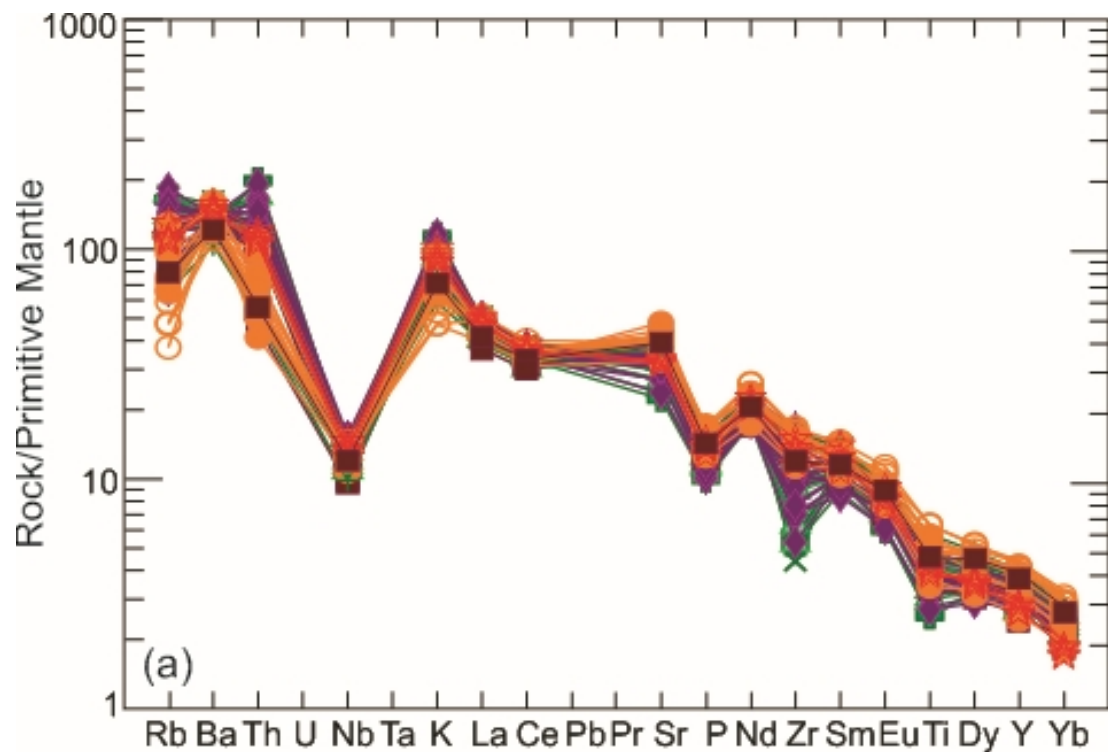












Supplementary material 1

The eruptive chronology of the Yucamane-Calientes compound volcano: a potentially active edifice of the Central Andes (Southern Peru)

Description of methods

Major and trace element whole-rock data

Major and trace element were determined at the Institut Universitaire Européen de la Mer (Brest, France), following the analytical procedure of [Cotten et al. \(1995\)](#). Typically 250 mg of rock powder were dissolved in closed screw-top teflon vessels (Savillex) at about 90°C for one day using 3 ml of concentrated HF, and 1 ml of concentrated HNO₃. Next, 96 ml of H₃B₃O₃ aqueous solution (20 g/L H₃B₃O₃) were added to neutralize the excess HF. All reagents used are analytical grade. Elements were measured by inductively coupled plasma-atomic emission spectrometry (ICP-AES) using a Horiba Jobin Yvon® Ultima 2 spectrometer. The boron included in the solution was used as an internal standard. Calibrations were made using international standard, ACE, ME, WSE, JB2. For major elements, relative standard deviation is ≤1% for SiO₂ and ≤2% for the other major elements, for trace elements standard deviation is ≤5%.

⁴⁰K-⁴⁰Ar geochronology

After macroscopic and microscopic inspections, groundmass from fresh samples was prepared following methods detailed in [Guillou et al. \(1998\)](#). The groundmass is assumed to have formed shortly after eruption and is unlikely to contain any significant excess argon. All the samples were crushed and sieved to 0.250-0.125 mm size fractions and ultrasonically washed in acetic acid (1N) during 45 minutes at a temperature of 60°C, to remove any secondary mineral phases that might be present in minute

amounts. Phenocrysts which are potential carriers of extraneous ^{40}Ar (including excess and inherited components) were filtered out using magnetic, gravimetric, and visual hand picking separation.

The isotopic composition and abundance of Ar were determined using an unspiked technique described by Charbit et al. (1998). In the unspiked technique, argon extracted from the sample is measured in sequence with purified aliquots of atmospheric argon at comparable working gas pressure in the mass-spectrometer, to suppress mass discrimination effects between the atmospheric reference and the unknown. This approach allows young samples to be dated reliably, as demonstrated via direct comparisons with the $^{40}\text{Ar}/^{39}\text{Ar}$ dating method (Guillou et al., 2004; Guillou et al., 2011; Singer et al., 2008; Singer et al., 2014). Aliquots of groundmass were separated by means of densitometric and magnetic separations following the procedure described in Guillou et al. (1998). Determination of K was carried out at the CRPG (Nancy, France) by atomic absorption (flame photometry) with a relative precision of 1%. Argon was extracted by radio frequency heating of 0.5 – 2.0 g of sample, then transferred to an ultra-high-vacuum glass line and purified with titanium sponge and Zr-Ar getters. Isotopic analysis was performed on total ^{40}Ar contents ranging between 1.0 and 5.9×10^{-11} moles using a 180° , 6 cm radius mass spectrometer with an accelerating potential of 620V. The mass spectrometer sensitivity is 5.2×10^{-1} mol/A @ $m/e = 40$ with amplifier backgrounds of 5×10^{-14} A @ $m/e = 40$ and 1.0×10^{-15} A @ $m/e = 36$. Beam sizes were measured simultaneously on a double Faraday collector in sets of 100 on-line acquisitions with a 1 s integration time, using two Keithley Model 6514 System Electrometers. A manometrically calibrated dose of atmospheric argon (cal. Dose) is used to convert beam intensities into atomic abundances. This dose, when comparable in pressure with the unknown, or a separate measurement of atmospheric argon (atm.

Ref.) is used to monitor the atmospheric correction. The manometric calibration is based on periodic, replicate determinations of international dating standards of known K-Ar age using the same procedure for the unknown samples to be measured, as described in [Charbit et al. \(1998\)](#). This allows the total ^{40}Ar content of the sample to be determined with a precision of about $\pm 0.2\%$ (2σ). Standards used include LP-6 (127.8 ± 0.7 Ma, [Odin et al., 1982](#)) and HD-B1 (24.21 ± 0.32 Ma, [Fuhrmann et al., 1987](#); [Hess and Lippolt, 1984](#); [Hautmann and Lippolt, 2000](#)). At the 95% confidence level, the values adopted here are consistent with those obtained for several $^{40}\text{Ar}/^{39}\text{Ar}$ standards through the intercalibration against biotite GA-1550 by [Renne et al. \(1998\)](#) and [Spell and McDougall \(2003\)](#). Uncertainties for the K and Ar data are 1σ analytical only, and consist of propagated and quadratically averaged experimental uncertainties arising from the K, ^{40}Ar (total), and $^{40}\text{Ar}^*$ determinations. Uncertainties on the ages are given at 2σ .

^{40}Ar - ^{39}Ar geochronology

Samples were crushed and sieved to the 400 μm -250 μm fraction size. After ultrasonic cleaning in acetic acid (1N) for 45 minutes at a temperature of 60°C , feldspars were concentrated through several density separations using Lithium Meta Tungstate (LMT) heavy liquid. Pristine feldspars crystals ranging from 250 μm up to 400 μm were handpicked under a binocular microscope and then slightly leached for 5 min in a 7% HF acid solution in order to remove adhered groundmass. A total of about 50 grains were finally handpicked and available for ^{40}Ar - ^{39}Ar laser total fusion experiments. Feldspars were irradiated in the CLICIT facility at the Oregon State University TRIGA reactor for 120 minutes (Irr#CO001) or 60 minutes (Irr#CO003). After irradiation, crystals were transferred into a copper sample holder and then loaded

into a differential vacuum Cleartran window. Prior to the fusion, all crystals were degassed at 4% of the laser power to remove potential atmospheric component that could be found at the surface and/or in the feldspar fractures. For each experiment, a crystal was molten using a focused 25 W CO₂ laser (Synrad) at about 10% of the full laser power. Extracted gas was purified by two GP-50 getter pumps one operating at 250°C, the second being at room temperature. The purified gas is then measured using a high-sensitivity noble gas GV5400 instrument operated in ion counting mode.

Neutron fluence (J) was monitored by co-irradiation of ACs-2 crystals (Nomade et al., 2005) placed in three pits encircling the sample. 2 ACs-2 crystal of each pit were analyzed and the J value was the arithmetic average of these 6 single crystal laser fusion analyses. It is reported in Supplementary Tables 2 along with the correction factors for interfering neutron reactions. Corresponding J values were calculated using an age of 1.1891 ± 0.0008 Ma (Niespolo et al., 2017). The total decay constants of Renne et al (2010, 2011) and the ⁴⁰Ar/³⁶Ar atmospheric ratio at 298.56 (Lee et al., 2006) were used for age calculations. The precision and accuracy of the mass discrimination correction was monitored by periodical measurements of air argon. This monitoring is performed using a dedicated air-calibration system featuring a 6 liters tank filled with purified atmospheric argon. This tank is connected to the mass spectrometer vacuum line via two pneumatically- actuated air pipettes of approximately 0.1 and 1.0 cc. This system allows for a 1 cc and a 0.1 cc atmospheric aliquots to be delivered into the mass spectrometer and permits a careful monitoring of the mass discrimination over a wide dynamic range with a precision better than 0.15% (2σ; standard deviation for multiples of experiments) for any given bean size measured.

U-Pb geochronology

Zircons were separated at the Laboratoire Magmas and Volcans (LMV Clermont-Ferrand, France) using standard techniques of crushing and sieving, followed by Wilfley table, magnetic separation and heavy liquids before handpicking under binocular microscope. They were mounted in epoxy disks and ground and polished at 0.25 μ m to expose crystal interiors. U-Th-Pb isotopic data on zircons were obtained by laser ablation inductively coupled plasma spectrometry (LA-ICP-MS) at the LMV and reported in Supplementary Material 3. The analyses involved the ablation of minerals with a Resonetics M-50 excimer laser system operating at a wavelength of 193 nm. Spot diameters of 60 μ m were associated to repetition rates of 4 Hz and fluency of 3.0 J/cm². The ablated material was carried into helium and then mixed with nitrogen and argon before injection into the plasma source of a Thermo Element XR Sector Field ICP-MS. The alignment of the instrument and mass calibration were performed before every analytical session using the NIST SRM 612 reference glass, by inspecting the signals of ²³⁸U, ²³²Th and ²⁰⁸Pb and by minimising the ThO⁺/Th⁺ ratio. The analytical method for isotope dating with laser ablation is basically similar to that reported in [Paquette et al. \(2014\)](#) and adapted to the analysis of Pliocene-Pleistocene zircons ([Paquette et al., 2019](#)). The ²³⁵U signal is calculated from ²³⁸U on the basis of the ratio ²³⁸U/²³⁵U = 137.818 ([Hiess et al., 2012](#)). Single analyses consisted of 30 seconds of background integration with laser off followed by 1 minute integration with the laser firing.

Data are corrected for U-Pb fractionation and for instrumental mass bias by standard bracketing with repeated measurements of GJ-1 zircon standard ([Jackson et al., 2004](#)). Repeated analyses of 91500 zircon reference material ([Wiedenbeck et al., 1995](#)) during each analytical session and treated as unknown, independently control the reproducibility and accuracy of the corrections. Data reduction was carried out with the software package GLITTER® from Macquarie Research Ltd ([van Achterbergh et al.,](#)

2001; Jackson et al., 2004). Common Pb and initial disequilibria caused by $^{230}\text{Th}/^{238}\text{U}$ and $^{231}\text{Pa}/^{235}\text{U}$ fractionation in the zircon/melt system were corrected according to Sakata et al. (2017) and Sakata (2018) method and related Microsoft Excel® spreadsheet. The concentrations in U-Th-Pb were calibrated relative to the certified contents of GJ-1 zircon (Jackson et al., 2004) reference material. The available fractionation factor of Pa/U in a zircon-melt system of rhyolitic composition roughly shows agreement with a value of 2.9 ± 1.0 (Sakata, 2018). This value and related uncertainty is propagated into the calculations. Weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages were generated using Isoplot/Ex v. 2.49 software package by Ludwig (2001).

^{14}C geochronology

Before ^{14}C measurement, samples were examined under a binocular microscope with the aim of eliminating any potential contaminant such as sand and roots. Then, the samples were chemically pre-treated to remove contaminants, in order to isolate a suitable fraction for dating. The treatment (referred to as the “AAA” treatment) consists of the following steps: (1) acid (HCl) leaching to remove soil carbonate; (2) alkali (NaOH) leaching to remove humic acids; and, (3) acid (HCl) leaching to remove any “modern” CO_2 absorbed during the previous steps. Variable amounts of the dried sample were used to obtain, after combustion, a CO_2 volume equivalent to at least 1 mg of C. Then, CO_2 is reduced by H_2 in the presence of iron powder. ^{14}C activity is finally measured by mass spectrometry. The ^{14}C ages are calculated following the procedure of Mook and van der Plicht (1999) and corrected for mass dependent effects (isotope fractionation) using the measured $^{13}\text{C}/^{12}\text{C}$ ratio. This $\delta^{13}\text{C}$ includes the fractionation which occurred both during sample preparation and measurement.

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