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1 **Late Cretaceous felsic intrusions in oceanic plateau basalts in SW Ecuador: markers of**  
2 **subduction initiation?**

3

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17 *Key words:* Caribbean oceanic plateau, tonalite, subduction initiation, SW Ecuador

18

19 **Abstract**

20

21 Felsic magmatic rocks (tonalites and trondhjemites) with calc-alkaline affinity were  
22 emplaced in SW Ecuador (Pascuales area; North Guayaquil) at ~87–89 Ma intruding the top

23 of the basalts of the Caribbean Large Igneous Province (CLIP), prior to the development of  
24 typical well-known island arcs from ~85-80 Ma onwards. A clear depletion of REE  
25 distinguishes the Pascuales felsic rocks from the more differentiated lavas of the Rio Cala Arc  
26 in Ecuador and from other Late Cretaceous arc-like felsic intrusives emplaced within the  
27 CLIP in Colombia and the Antilles. In addition, the Pascuales tonalites have very low  $K_2O$  (<  
28 0.4 wt.%),  $TiO_2$  (< 0.4 wt.%) and  $P_2O_5$  (< 0.15 wt.%) contents compared to dacitic rocks of  
29 the Rio Cala Arc. In contrast, their geochemistry and their similar age suggest that the  
30 Pascuales tonalites are an equivalent of the Las Orquideas dacitic volcanic rocks. The  
31 Pascuales felsic rocks have the less radiogenic Nd compositions of the whole spectrum of  
32 Ecuadorian oceanic plateau rocks, nevertheless showing similarities with some Totoras  
33 amphibolites. The geochemical characteristics of the Pascuales intrusives and Las Orquideas  
34 dacites are similar to those formed by hydrous partial melting of mafic protoliths. The dacitic  
35 magmas must have been in equilibrium with residual mineral assemblages largely dominated  
36 by amphibole + Fe–Ti oxides (no garnet). This requires two conditions: 1) low-pressure  
37 melting under high water content and 2) a source rock extremely depleted in minor  
38 incompatible elements (K, Ti, P, Y) and REE. These conditions are fulfilled by partial melting  
39 of mafic-ultramafic cumulates undergoing high temperature and shear deformation at the base  
40 of the oceanic plateau triggered by new basaltic intrusions. The Pascuales felsic rocks  
41 emplaced at the SW border of the oceanic plateau during its final stage of building; they can  
42 thus be related to asthenospheric upwelling during the initial stage of island arc magmatism.

43

## 44 **1. Introduction**

45

46 The Caribbean Large Igneous Province (CLIP; Fig. 1) is an oceanic terrane currently  
47 exposed in the Caribbean region and in northwestern South America. The CLIP mainly

48 extruded between 100 Ma and 88 Ma (e.g. Kerr et al., 2003; Luzieux et al., 2006; Sinton et  
49 al., 1998; Villagómez et al., 2011; Wattam and Stern, 2015), although significantly younger  
50 rocks up to circa 65 Ma have been observed in the Gorgona Island and Western Colombia  
51 (Serrano et al., 2011; Sinton et al., 1998). The origin of the CLIP is also debated with theories  
52 proposing an extrusion in a location close to the paleo-Galapagos hot spot (e.g. Duncan et al.,  
53 1984; Whattam and Stern, 2015) or an origin related to a different plume event (e.g.  
54 Boschman et al., 2014). The borders of the CLIP are characterized by plateau basaltic rocks  
55 and tonalitic magmatism, the latter being ascribed to the melting of the plateau or to incipient  
56 subduction processes (e.g. White et al., 1999; Wright and Wyld, 2011; Villagomez et al.,  
57 2011; Whattam and Stern, 2015; Weber et al., 2015). Because of its high buoyancy and  
58 thickness (between 8 and >20 km; Kerr et al., 2003) it is believed that the CLIP (and an  
59 associated island arc) accreted to the South American margin between 80 Ma and 65 Ma  
60 (Vallejo et al., 2009; Villagómez et al., 2011; Kerr et al., 2002a; Hughes and Pilatasig, 2002;  
61 Jaillard et al., 2009).

62 Rocks from the southern limit of the CLIP in SW Ecuador include: 1) basalts, dolerites and  
63 gabbros typical of plateau settings with ages ranging between 90 Ma and 85 Ma (Kerr et al.,  
64 2002a; Luzieux et al., 2006; Vallejo et al., 2009, 2006), an interval that coincides with the  
65 major pulse of CLIP magmatic activity and with the supposed plume-induced subduction  
66 initiation at the margins of the CLIP, and 2) Late Cretaceous intrusive and volcanoclastic  
67 deposits (with ages also roughly coincident with the suggested subduction initiation beneath  
68 the CLIP) that have geochemical affinities that may relate them to a juvenile subduction  
69 setting (see also the bachelors thesis of Macias, 2018). However, various works in southwest  
70 and central Ecuador (Allibon et al., 2008; Amórtegui et al., 2011; van Melle et al., 2008)  
71 suggest that similar geochemical characteristics may result from the partial melting of the  
72 base of the oceanic plateau. Farther north, in the Western Cordillera of Ecuador, La Portada

73 Unit assigned to the base of the Rio Cala island arc (Kerr et al., 2002a; van Thournout, 1991;  
74 Wilkinson, 1998) and the Pujilí Granite (PG in Fig. 2) have been ascribed to the oldest  
75 evidences of subduction beneath the CLIP in Ecuador at ~85 Ma (Vallejo, 2007; Vallejo et  
76 al., 2009).

77 In the SW Ecuadorian forearc region, the CLIP rocks crop out at the Chongón-  
78 Colonche Hills (CCH, Figs. 1 and 2). The CCH hills are defined by a major positive  
79 gravimetric anomaly probably related to crustal thinning (the crust is only ~7 km thick versus  
80 ~15 km in average in the forearc) and resulting mantle upwelling (Aizprua et al., 2020).  
81 Several small tonalitic, gabbroic and ultramafic bodies intrude the CLIP rocks close to the  
82 area where the CCH is buried westwards beneath the Plio-Quaternary sedimentary cover (Fig.  
83 2; Pichler and Aly, 1983; Benitez, 1995; Eguez et al., 2017). These intrusions were poorly  
84 studied in the past and, in addition, most outcrops are now extensively covered by new civil  
85 constructions. Tonalitic intrusive bodies located near the town of Pascuales (Fig. 3A) have  
86 reported K-Ar ages of  $73.3 \pm 4.8$  Ma (Pichler and Aly, 1983) similarly to other circa K-Ar 70  
87 Ma cooling ages that can be arguably interpreted as a thermal cooling event related to the  
88 collision of the CLIP onto South America (e.g. Aspden and Litherland, 1992). To date, there  
89 are no published geochemical nor geochronologic constrains for the intrusive rocks located  
90 near the town of Pascuales, which is unfortunate because they might help unravel part of the  
91 youngest Cretaceous geodynamic processes that occurred in SW Ecuador. In this work we  
92 present the results of in situ LA-ICP-MS U-Pb dating on zircon and new petrographic,  
93 geochemical and isotopic analyses on felsic intrusions sampled near Pascuales (Fig. 3A), as  
94 well as new geochemical and isotopic whole rock analyses on the country basaltic rocks.  
95 These data allow us to chemically characterize a group of intermediate to felsic magmatic  
96 rocks with calc-alkaline affinity, which emplaced at ~87–89 Ma at the top of the CLIP basalts  
97 (i.e. prior to the development of Late Cretaceous island arcs). In this context, the new data

98 presented here is combined with previously published analyses for plateau and island arc  
99 suites in Ecuador (i.e., Las Orquideas Member, Rio Cala Arc, San Lorenzo Formation) and  
100 Colombia in order to discuss the possible origins of these arc-like rocks, as well as their  
101 relations with the country-rock oceanic plateau basalts and resulting geodynamic  
102 implications.

103

## 104 **2. Geological context**

105

106 The Andean chain in Ecuador shows two distinctive Eastern and Western Cordilleras  
107 in which topographic growth most likely took place during the last 75-70 Ma (Gutiérrez et al.,  
108 2019; Spikings et al., 2010; Witt et al., 2017). The basement of the forearc and Western  
109 Cordillera (WC) is made up of oceanic plateau basalts (herein referred as OPB) which were  
110 accreted to the continental margin of South America. These accreted terrains have been  
111 ascribed to the Piñón, Pallatanga, San Juan and Guaranda terranes, units or formations (Fig. 2;  
112 Hughes and Pilatasig, 2002; Jaillard et al., 2009; Kerr et al., 2002a; Mamberti et al., 2003;  
113 Vallejo et al., 2009). The definition of the nature, number and timing of accretion events has  
114 been one of the most debated topics in the Ecuadorian geology for the last 30 years. For some  
115 authors, a single Caribbean type accretion occurred between 75-65 Ma (Luzieux et al., 2006;  
116 Vallejo et al., 2009; Chiaradia, 2009) whereas other studies suggest multi-episodic oceanic  
117 accretions (some of them with no Caribbean affinities) at ~75 Ma, ~68 Ma and ~58 Ma, and  
118 even early Eocene (e.g. Feininger, 1987; Hughes and Pilatasig, 2002; Jaillard et al., 2009;  
119 Kerr et al., 2002a; Aizprua et al., 2019). The debate is mostly originated by differences in the  
120 subduction polarity and the age of some oceanic rocks ascribed to the San Juan Formation  
121 (see below). Accretional events are believed to represent one of the main driving factors for  
122 the generation of relief in the Ecuadorian Andes (Jaillard et al., 2009; Witt et al., 2017).

123                   The Piñón Formation (Fm.) represents the mafic plume-related basement of the  
124 Ecuadorian forearc and is mainly composed of tholeiitic, massive and pillowed basaltic and  
125 basalt–andesitic lavas, locally intruded by dolerites and/or gabbroic stocks (e.g. Kerr et al.,  
126 2003; Reynaud et al., 1999). In the CCH, the top of the Piñón Fm. has been ascribed to the  
127 lower part of the Coniacian (i.e. ~90 Ma) based on planktic foraminifera and radiolarians  
128 collected in cherts intercalated between pillow lavas and on the age of the overlying Calentura  
129 Fm. (Ordoñez et al, 2006; van Melle et al., 2008; Velasco and Mendoza, 2003). Furthermore,  
130 a gabbro within the Piñón Fm. yielded a hornblende  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age of  $88.8 \pm 1.6$  Ma  
131 (Luzieux et al., 2006). The CCH is defined by one of the most significant gravimetric positive  
132 anomalies in the Northern Andes which most likely resulted from significant crustal thinning  
133 (the crust is only ~7 km thick in the CCH) and related denudation and mantle upwelling  
134 (Aizprua et al., 2020).

135                   In the Western Cordillera, the Pallatanga / Guaranda Unit (92–88 Ma, Fig. 2; Kerr et  
136 al., 2002b; Kerr et al., 2003), likely also a fragment of the CLIP, is petrographically and  
137 geochemically similar to the Piñón basalts and dolerites (Kerr et al., 2002a; Mamberti et al.,  
138 2003). To the east of the Western Cordillera (Fig. 2), cumulate peridotites and gabbros  
139 intruded by mafic and felsic dykes of the San Juan Unit crop out as tectonic slices entrained  
140 within the Late Cretaceous ocean-continent suture (Hughes and Bermudez, 1997; Fig. 2). This  
141 unit is either interpreted as the root of the Pallatanga Unit (Lapierre et al., 2000; Hughes and  
142 Pilatasig, 2002) or as a magmatic chamber within the oceanic plateau (Mamberti et al., 2004).  
143 A gabbro of the San Juan Unit (SJG in Fig. 2) yielded a zircon U-Pb age of  $87.1 \pm 1.6$  Ma  
144 interpreted as the crystallization age (Vallejo et al., 2006), comparable to the  $88.8 \pm 1.6$  Ma  
145  $^{40}\text{Ar}/^{39}\text{Ar}$  age obtained from the Piñón hornblende gabbro by Luzieux et al. (2006). Similarly,  
146 in the Tortoras area (TA in Fig. 2) one amphibolite yielded an age of  $84.7 \pm 2.2$  Ma ( $^{40}\text{Ar}/^{39}\text{Ar}$   
147 in hornblende interpreted as a cooling age following amphibolite facies metamorphism prior

148 to the accretion of the oceanic plateau (Vallejo et al., 2006). However, an age obtained from  
149 gabbroic units also ascribed to the San Juan unit yielded a Sm/Nd isochron of  $123\pm 13$  Ma  
150 (Lapierre et al., 2000); suggesting that these rocks represent an older eruptive phase of the  
151 plateau and most likely an older accretionary process. Indeed, Miocene transpressive faults  
152 crosscutting the Western Cordillera also exhumed mafic granulites and amphibolites with  
153 geochemical and Nd isotopic compositions characteristic of oceanic plateau basalts (Jaillard  
154 et al., 2004; Beaudon et al., 2005; Amortegui et al., 2011), which differ from the Pallatanga  
155 Unit and Piñón Fm. because they have Pb isotopic features similar to those of the Late  
156 Cretaceous intra-oceanic arc (Amortegui et al., 2011).

157 In SW Ecuador, the Piñón Fm. is mostly overlain by magmatic or volcanoclastic  
158 successions with island arc affinities ascribed to the Santonian Cayo and Campanian-  
159 Maastrichtian San Lorenzo Fms., the latest cropping out at the NE directed Coastal Cordillera  
160 (Lebrat et al., 1987; Luzieux et al., 2006; van Melle et al., 2008; Reynaud et al., 1999; Figs. 1  
161 and 2). However, in the CCH to the west of Guayaquil, a thin layer of volcanic rocks referred  
162 to as the Las Orquideas (LO) Member is intercalated between the Piñón basalts and the  
163 Calentura and Cayo sedimentary and volcanoclastic deposits (Reynaud et al., 1999; van Melle  
164 et al., 2008). The LO Member is a 30 to 150 m thick lava sequences mainly composed of  
165 explosive, intermediate to dacitic products (Benitez, 1995; Reynaud et al., 1999; van Melle et  
166 al., 2008). Pelagic microfauna in interbedded limestones allowed attribution of the LO  
167 volcanism to the Middle Coniacian (~88 Ma; van Melle et al., 2008 and references therein).  
168 Despite the calc-alkaline signature of the LO rocks, van Melle et al. (2008) considered that  
169 their emplacement in a subduction setting was very unlikely mainly because the generation of  
170 arc magma at ~ 100 km depth and its ascent to the surface would require more than the  
171 observed ~2 Ma time interval between the end of plume activity and the eventual formation of  
172 the subduction zone (i.e. with respect to the 85 Ma Pujili granite). Furthermore, these authors



173 suggested that the small volume of the volcanic cover is atypical for an island arc setting.  
174 Instead, these authors proposed that the LO volcanic rocks were generated by partial melting  
175 of deep parts of the CLIP.

176         In the Western Cordillera, arc sequences developed on top of the oceanic plateau (Fig.  
177 2), both before and after their accretion(s) onto the continent. The Rio Cala Group (Santonian  
178 to early Maastrichtian; Hughes and Bermúdez, 1997; Boland et al., 2000) and its tholeiitic Rio  
179 Cala island arc ( $66.7 \pm 7.2$  Ma Ma, Vallejo et al., 2009) represents the oldest clear evidence of  
180 arc magmatism observed in the Western Cordillera, yet its original position may have been  
181 related to either westwards (e.g. Vallejo et al., 2009) or eastward (e.g. Jaillard et al., 2009)  
182 subduction prior to the main accretional period 75-65 Ma ago (Vallejo et al., 2009; Chiaradia,  
183 2009). An older age of  $85.5 \pm 1.4$  Ma (zircon LA-ICP-MS U-Pb age; Vallejo et al., 2006) was  
184 obtained for the Pujilí Granite, which occurs within a tectonic block within the continent -  
185 ocean suture, east of the Western Cordillera (PG in Fig. 2). The adakitic nature of the Pujilí  
186 Granite and some plume-like mineralogical and geochemical characteristics of the Late  
187 Cretaceous arc magmatism in SW Ecuador suggest a hot subduction zone, which possibly  
188 facilitated the incorporation of a mantle plume component in the arc magmas through  
189 assimilation and/or partial melting of the CLIP (Allibon et al., 2008; Vallejo et al., 2009).  
190 According to Whattam and Stern (2015), all Late Cretaceous magmatic events (i.e. post-100  
191 Ma) in Southern Ecuador correspond to hybrid magmas with both plume and subduction zone  
192 contributions, with a progressive increasing amount of subduction-related magma in the  
193 hybrid plume-mantle source.

194

195

### 196 **3. Sampling and analytical methods**

197

198           Samples of this study were collected north of Guayaquil in the easternmost border of  
199 the CCH (Fig. 2), near the town of Pascuales (Fig. 3A) where intrusions of felsic plutonic  
200 rocks occur within ~2-4 km long ~ 1.5 km wide areas (red outlines in Fig. 3A). The best two  
201 preserved outcrops show subhorizontal, ~5 m thick, layers of massive, greenish to grey pale  
202 rocks affected by numerous orthogonal fractures. One of the outcrops (Fig. 3B) provided two  
203 pieces of trondhjemites (GD001 and GD002) forming the lower layer, while three tonalite  
204 pieces were sampled in the upper layer (GD003, CP601, CP024). A fourth trondhjemitic  
205 sample (CP603) was collected in the second outcrop (Fig. 3C). Rocks surrounding the felsic  
206 intrusions are medium to fine grained basalts and metabasalts showing variable degrees of  
207 mylonitization and alteration. Locally, they are cross-cut by hornblende-filled shear zones,  
208 and veinlets or microdykes composed of dioritic mineral assemblages (plagioclase,  
209 magnesiohornblende and opaque minerals). Least altered volcanic mafic rocks were also  
210 sampled at different locations (CP605, CP607, GD004; Fig. 3A). Mineral compositions of  
211 selected samples were determined with a CAMECA SX100 electron microprobe with 4  
212 wavelength-dispersive spectrometers at the Ecole Nationale Supérieure de Chimie in Lille  
213 University. Analytical conditions were 15 kV acceleration voltage, 15nA beam current and a  
214 peak counting time of 20s. Natural standards were used for the electron microprobe  
215 calibration. Zircon U-Pb geochronology was conducted by in-situ laser ablation inductively  
216 coupled plasma mass spectrometry (LA-ICP-MS) at the GeOHeLiS analytical platform  
217 (Géosciences Rennes/OSUR, Univ. Rennes) using an ESI NWR193UC Excimer laser coupled  
218 to a quadrupole Agilent 7700x ICP-MS equipped with a dual pumping system to enhance  
219 sensitivity. Concordia ages and diagrams were generated using Isoplot/Ex (Ludwig, 2012).  
220 Operating conditions are presented in Table S1. For a more detailed description of the  
221 analytical protocol see Manzotti et al. (2015) and Witt et al. (2019). Whole-rock compositions

222 were obtained by fusion technique (lithium metaborate/tetraborate). Diluted solutions were  
223 analyzed for major oxides by Inductively-Coupled Plasma Optical Emission Spectrometry  
224 (ICP-OES) and by Inductively-Coupled Plasma Mass Spectrometry (ICP-MS) for trace  
225 elements, at the Actlabs laboratory (Ontario, Canada) according to code 4Lithoresearch  
226 package. The international standards used for analytical control were BIR-1a (basalt), DCN-1  
227 (dolerite), GBW 07113 (rhyolite), TDB-1 (diabase rock), DTS-2b (dunite), SY-4 (diorite  
228 gneiss), NCS DC86312 (rare earth ore) CTA-AC-1 (apatite concentrate). for further details,  
229 see <http://www.actlabs.com>.

230 Radiogenic isotope ratios of Sr ( $^{87}\text{Sr}/^{86}\text{Sr}$ ), Nd ( $^{143}\text{Nd}/^{144}\text{Nd}$ ) and Pb ( $^{206}\text{Pb}/^{204}\text{Pb}$ ,  
231  $^{207}\text{Pb}/^{204}\text{Pb}$ ,  $^{208}\text{Pb}/^{204}\text{Pb}$ ) were measured at the Department of Earth Sciences (University of  
232 Geneva, Switzerland). The method is described in detail in Chiaradia et al. (2020). Briefly,  
233 100 to 120 mg of whole rock powder were dissolved in concentrated HF and HNO<sub>3</sub>. Samples  
234 were dried and re-dissolved in concentrated HNO<sub>3</sub> and dried again. Sr, Nd and Pb were then  
235 separated using cascade columns with Sr-Spec, TRU-Spec and Ln-Spec resins according to a  
236 protocol modified from Pin et al. (1994). The material was finally redissolved in 2% HNO<sub>3</sub>  
237 solutions and ratios were measured using a Thermo Neptune PLUS Multi-Collector ICP-MS  
238 in static mode. Long-term (>2 years) reproducibility of SRM987 (McArthur et al., 2001),  
239 JNdi-1 (Tanaka et al., 2000) and SRM981 (Baker et al., 2004) standards are 10 ppm (1SD) for  
240  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$ , 0.0048% for  $^{206}\text{Pb}/^{204}\text{Pb}$ , 0.0049% for  $^{207}\text{Pb}/^{204}\text{Pb}$  and 0.0062%  
241 for  $^{208}\text{Pb}/^{204}\text{Pb}$ .  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$  and Pb isotope ratios were corrected for external  
242 fractionation (due to a systematic difference between measured and accepted standard ratios)  
243 by a value of -0.021‰, +0.051‰ and +0.36‰ amu respectively. Total procedural blanks  
244 were <500 pg for Pb and <100 pg for Sr and Nd which are insignificant compared to the  
245 amounts of these elements purified from the whole rock samples investigated.

246

247

## 248 **4. Petrography and mineralogy**

249

### 250 *4.1. Felsic rocks*

251

252 Samples CP601, CP024, GD003 are medium-grained tonalites composed of quartz  
253 (~27–32 vol.%), plagioclase (~50–55 vol.%) and green amphibole (~10–12 vol.%;  
254 supplementary Fig. S1A). Plagioclase and amphibole occur as euhedral-subhedral prismatic  
255 crystals, while quartz is mainly present in a granular mosaic texture enclosing the former  
256 minerals. Apatite, titanite, zircon and titanomagnetite are accessory minerals. Plagioclase  
257 grains are zoned with Ca-rich cores and Na-rich rims; their compositions range from  
258  $An_{55}Ab_{44}Or_1$  to  $An_7Ab_{88}Or_4$  (average  $An_{39.6}Ab_{59.0}Or_{1.4}$ ;  $n = 27$ ). Dark green  
259 magnesiohornblende forms stubby, commonly twinned, prismatic crystals, locally replaced by  
260 actinolite. Minor amounts of epidote, chlorite and magnetite also occur as intergranular  
261 phases and as inclusions in the magnesiohornblende cores where they may represent former  
262 pyroxenes. Samples CP603 (Fig. S1B), GD001 and GD002 mostly consist of euhedral-  
263 subhedral albite ( $Ab_{99\pm 1}$ ;  $n = 17$ ) and quartz in near equal amounts, and correspond to  
264 trondhjemites following the definition of Barker (1979). Textures are hipidiomorphic granular  
265 to granophyric (e.g., graphic intergrowths of quartz and albite forming almost 20 vol.% of the  
266 rocks). Primary mafic minerals (up to 7 vol.%, likely former amphiboles) are replaced by  
267 chlorite, Fe-oxides and epidote group minerals. Titanomagnetite  $\pm$  ilmenite, titanite and zircon  
268 occur as accessory phases.

269

### 270 *4.2. Mafic rocks*

271

272 *4.2.1 Petrography*

273

274           Sample CP605 (Fig. S1C) is a dark green, fine-grained, undeformed and homogeneous  
275 metabasite. Rare, euhedral to subhedral, clinopyroxene phenocrysts (400–600  $\mu\text{m}$  in diameter;  
276 ~1 vol.%) are fully pseudomorphosed by green amphiboles. Groundmass is intersertal-  
277 intergranular, composed of skeletal plagioclase laths ( $\text{An}_{41\pm 11}$ ;  $n = 38$ ), clinopyroxene grains  
278 partially replaced by amphibole, and accessory ilmenite, titanomagnetite, apatite and pyrite.  
279 Sheaf-like radial clusters of plagioclase are also observed. Low-grade secondary minerals  
280 form less than 5 vol.% and are represented by chlorite, albite, epidote, titanite, biotite and  
281 magnetite. Sample CP607 (Fig. S1D) shows a cataclastic structure but has preserved  
282 undeformed parts with igneous texture that are large enough to be analyzed. Igneous texture is  
283 sparsely phyrlic (<1 vol.%) with ~1–2 mm sized, subhedral pseudomorphs of clinopyroxene  
284 phenocrysts fully replaced by brownish to dark green amphiboles. They have spongy cores  
285 enclosing groundmass and are surrounded by ~100  $\mu\text{m}$  - thick corona also replaced by  
286 amphiboles whose shapes and color are similar to those in the cores but oriented differently.  
287 Groundmass is holocrystalline, medium-grained (400–600  $\mu\text{m}$ ), made of plagioclase laths  
288 partially albitized and clinopyroxenes replaced by amphibole, titanite and magnetite.  
289 Accessory ilmenite and titanomagnetite are widespread in groundmass. Other low-grade  
290 secondary minerals (< 5 vol.%) are albite, chlorite, magnetite, quartz, epidote group minerals  
291 and biotite. Sample GD004 (Fig. S1E) is a medium-grained (200–700  $\mu\text{m}$ ), isogranular basalt  
292 made of plagioclase, clinopyroxene and abundant, up to 150  $\mu\text{m}$  sized crystals of ilmenite and  
293 titanomagnetite. Hydrothermal alteration is marked by replacement of plagioclase, pyroxene  
294 and Fe-Ti oxides by albite, diopside, epidote, titanite and crystallization of pyrite-  
295 chalcopyrite.

296

297 4.2.2. Mineral chemistry

298

299 Fresh clinopyroxenes (Table S2; Fig. 4A,B) have been only preserved in samples  
300 CP605 and GD004. In CP605 they are magnesian augites ( $\text{En}_{49.7\pm 0.9}\text{Wo}_{39.4\pm 0.9}\text{Fs}_{11.0\pm 0.8}$ ;  $n = 16$ )  
301 which show variable  $\text{Al}_2\text{O}_3$  contents ( $2.21 \pm 0.36$  wt.%) negatively correlated with Mg# [=  
302 molar  $\text{Mg}/(\text{Mg} + \text{Fe}_{\text{tot}}) = 83\text{--}80$ ]. Although somewhat scattered, GD004 clinopyroxenes are  
303 augites ( $\text{En}_{48.0\pm 0.5}\text{Wo}_{37.1\pm 0.6}\text{Fs}_{14.9\pm 0.7}$ ; Mg# 78–75;  $n = 36$ ) slightly poorer in  $\text{Al}_2\text{O}_3$  ( $1.93 \pm 0.14$   
304 wt.%).

305 Primary plagioclase compositions range from  $\text{An}_{59}$  to  $\text{An}_{24}$  ( $\text{An}_{42\pm 11}$ ;  $n=47$ ) in CP605  
306 and from  $\text{An}_{75}$  to  $\text{An}_{25}$  ( $\text{An}_{51\pm 16}$ ;  $n = 48$ ) in CP607. In both samples secondary albitic  
307 compositions ( $\text{An}_{9\pm 3}$  in CP605;  $\text{An}_{10\pm 2}$  in CP607) forming 12–15% of the analytical set are  
308 separated from the primary compositions by a compositional gap. In GD004 all the  
309 plagioclases are albitized.

310 Amphiboles are the major mafic phases in CP605 and CP607 and are absent in  
311 GD004. Their compositions calculated according to the 13-cations method (e.g. Leake et al.,  
312 1997; Ridolfi et al., 2010) are listed (Table S2). They are Ti-poor ( $\text{Ti} \leq 0.1$  apfu), Mg-rich  
313 [ $\text{Mg}/(\text{Mg} + \text{Fe}^{2+}) = 0.6\text{--}0.8$ ] calcic ( $[\text{Ca}]_{\text{B}} = 1.7\text{--}1.9$  apfu) amphiboles showing a large range  
314 of compositions (Fig. 4C). Aluminous end-member compositions ( $^{\text{IV}}\text{Al} = 1.6\text{--}2.0$  and  $[\text{Na} +$   
315  $\text{K}]_{\text{A}} = 0.46\text{--}0.58$ ) occur as small, relic inclusions within the less aluminous amphiboles (Fig.  
316 S1F). Their compositions are transitional between tschermakitic pargasite ( $^{\text{IV}}\text{Al} \geq 0.5$ ;  $[\text{Na} +$   
317  $\text{K}]_{\text{A}} < 0.5$ ) and magnesiohastingsite ( $^{\text{IV}}\text{Al} \geq 1.5$ ;  $[\text{Na} + \text{K}]_{\text{A}} \geq 0.5$ ) (Fig. 4D), indicating  
318 crystallization at high temperature (e.g.,  $\geq 850$  °C, Ridolfi et al., 2010 and therein references).  
319 Their low Ti contents suggest a metamorphic / hydrothermal origin (e.g. Coogan et al., 2001;

320 Gillis et al., 2001, Ridolfi and Renzulli, 2012 for a review). Furthermore, a small amount of  
321 chlorine was detected with the EDS (energy dispersive spectroscopy). Compositions of the  
322 other amphiboles vary from magnesiohornblende to actinolitic hornblende. In both samples,  
323 the wide compositional range, with decreasing <sup>IV</sup>Al (down to 0.5) positively correlated with  
324 decreasing alkali contents ([Na + K]<sub>A</sub> down to 0.02) (Fig. 4D), reflect crystallization at  
325 decreasing temperatures in lower to upper amphibolite facies conditions (~850–450°C,  
326 Anderson and Smith, 1995; Gillis and Roberts, 1999; Helz, 1982). Replacement of the  
327 pyroxenes thus started at high temperature under static conditions, likely reflecting  
328 seawater/hydrothermal alteration/metamorphism that occurred shortly after eruption, when  
329 the basalts were still hot. Amphiboles in veins crosscutting the basalts and associated with  
330 cataclasis are low-Al hornblende and actinolite.

331

## 332 **5. U–Pb dating of zircon**

333

334 Two tonalites (CP024 and CP601) and one trondhjemite (CP603) were selected for U-  
335 Pb dating. Results are reported in Table S3 and plotted in Fig. 5. Zircons vary from irregular  
336 with few developed faces to anhedral (Fig. S1G). They show little or no  
337 cathodoluminescence. For sample CP024, 18 analyses were performed on 18 different zircon  
338 grains. Plotted in a Tera-Wasserburg diagram (Fig. 5A), fifteen of them are concordant within  
339 error (plain line ellipses in Fig. 5A and in bold in Table S3) while three have a discordancy  
340 between 5 and 9% (dashed-line ellipses in Fig. 5A). These fifteen concordant data yield a  
341 concordia date (as of Ludwig, 1998) of  $89.6 \pm 2.0$  Ma (MSWD = 1.2) identical within error  
342 with the <sup>206</sup>Pb/<sup>238</sup>U weighted date of  $89.7 \pm 0.6$  Ma (MSWD = 0.75; n = 6). The position of  
343 the three remaining discordant analyses is attributed to the presence of a slight common Pb  
344 component together with a very small Pb loss (at least for analyses 25120314 and 30120314,

345 see Table S3 and Fig. 5A). Sample CP601 was collected on the same outcrop as sample  
346 CP024. In this case all the seventeen analyses are discordant (Fig. 5B). This discordancy is  
347 interpreted as the sign for the presence of initial (common) Pb in the analyzed zircon grains. If  
348 an isochron is anchored to a  $^{207}\text{Pb}/^{206}\text{Pb}$  initial value of 0.84 (calculated following then Stacey  
349 and Kramers (1975) Pb evolution model for an age of 90 Ma), the resulting lower intercept  
350 yields a date of  $87.2 \pm 1.3$  Ma (MSWD = 4.6; n = 17). Thirteen zircon analyses from sample  
351 CP603, plot in a concordant to discordant position (Fig. 5C) revealing different amount of  
352 initial (common) Pb in the grains. Five analyses are concordant within error (grey ellipses in  
353 Fig. 5C and in bold in Table S3) yield a concordia date of  $86.5 \pm 2.3$  Ma (MSWD = 4.8; n =  
354 5) while the whole set of data return a lower intercept date of  $85.3 \pm 1.0$  Ma (MSWD = 2.2; n  
355 = 13) if the isochron is anchored to a  $^{207}\text{Pb}/^{206}\text{Pb}$  initial value of 0.84. In the light of these  
356 data, we conclude that these felsic intrusives were emplaced 87-89 Ma ago.

357

## 358 **6. Elemental geochemistry**

359

360 Whole rock major element analyses were performed on five felsic and three basaltic  
361 samples. Results are presented in Table 1 and plotted in Fig. 6–9 along with analyses of Late  
362 Cretaceous (pre-collision) magmatic rocks from southwestern Ecuador for comparison (see  
363 Fig. 2 for their spatial distributions/positions). All compositions are recalculated as volatile-  
364 free and summing to 100%.

365

### 366 *6.1. Felsic rocks*

367



368 Consistent with their mineralogy, the five analyzed samples plot as tonalites (CP601  
369 and GD003) and trondhjemites (CP603, GD001, GD002) on Barker et al. (1979)'s Ab-An-Or  
370 diagram (Fig. 6). Loss on ignition (LOI) vary from 0.85 to 1.98 wt.%, in agreement with  
371 minor hydrothermal alteration and/or weathering. The abundances in major and trace  
372 elements are plotted against silica in Figs. 7 and 8, respectively. SiO<sub>2</sub> contents range from  
373 66.5–69.8 wt.% at 2.5–2.7 wt.% MgO in the tonalites to 78.0–80.1 wt.% at 0.3–0.6 wt.%  
374 MgO in the trondhjemites. The transition from tonalite to trondhjemite is marked by decreases  
375 of Fe<sub>2</sub>O<sub>3</sub>\* (~6.3 to 1.5–3.7 wt.%), Al<sub>2</sub>O<sub>3</sub> (~13.6 to 11.3 wt.%), CaO (~4.7 to 1.0 wt.%), P<sub>2</sub>O<sub>5</sub>  
376 (~0.07 to 0.03 wt.%), V (127 to 12 ppm, not shown) and Sr (~216 to 64 ppm). Inversely,  
377 Na<sub>2</sub>O (~4.1 to 5.2 wt.%), La (~4.4 to 5.6 ppm), Zr (~54 to 91 ppm), Nb (~1.7–2.2 ppm) and  
378 Th (~0.6–1.0 ppm) increase slightly. Both the tonalitic and trondhjemitic samples are  
379 characterized by extreme depletions in REE (3.7–6.2 ppm La; 0.65–0.85 ppm Yb) and Y  
380 (4.8–7.4 ppm). Compared to more differentiated lavas of the Rio Cala Arc, the Pascuales  
381 tonalites are distinctly depleted in K<sub>2</sub>O (< 0.3 wt.%), TiO<sub>2</sub> (< 0.3 wt.%) and P<sub>2</sub>O<sub>5</sub> (< 0.05  
382 wt.%) contents and are 21–26% more depleted in REEs and Y at 68–70 wt% SiO<sub>2</sub>. On the  
383 other hand, they are similar to the LO volcanic rocks having more than 57 wt.% SiO<sub>2</sub> (except  
384 one LO dacite which is enriched in K<sub>2</sub>O).

385 Chondrite-normalized (CN) REE abundances (Fig. 9A,B) of the Pascuales felsic rocks  
386 like those of LO dacites ( $\geq 63$  wt.% SiO<sub>2</sub>) exhibit flat HREE concentrations (Er/Y<sub>CN</sub> = ~1.0–  
387 1.1) followed by moderate enrichments in the more incompatible REE (La/Sm<sub>CN</sub> = 1.5–2.0  
388 and 1.7–2.2 in tonalite and dacite, respectively; La/Yb<sub>CN</sub> 3.6–4.7 in both rock types). In  
389 contrast, the Ho/Yb<sub>CN</sub> ratios in trondhjemite decrease progressively from ~1.0 in GD001 to  
390 0.7 in GD002, together with increasing enrichments in LREE relative to MREE (La/Sm<sub>CN</sub> =  
391 2.7–4.0) and HREE (La/Yb<sub>CN</sub> = 4.4–6.5); these chemical features are especially marked in the  
392 trondhjemitic sample GD002. The tonalites show moderate depletions in Eu relative to

393 adjacent REE ( $\text{Eu}/\text{Eu}^* = 0.80\text{--}0.86$ ), while the trondhjemite GD002 displays a pronounced  
394 positive Eu anomaly ( $\text{Eu}/\text{Eu}^* = 1.43$ ), reflecting plagioclase fractionation for the former and  
395 accumulation of sodic plagioclase for the latter. The other trondhjemitic samples lack any Eu  
396 anomaly.

397 On multi-element plots normalized to the Primitive Mantle (PM; Fig. 9C), all the  
398 silica-rich samples display subduction-like geochemical signatures characterized by negative  
399 Nb anomalies. However, Nb depletions relative to La are significantly less pronounced in the  
400 Pascuales intrusives and LO dacites ( $\text{Nb}/\text{La}_{\text{PM}} = 0.37 \pm 0.03$  and  $0.48 \pm 0.05$ , respectively)  
401 than in the silicic lavas from the Rio Cala Arc ( $\text{Nb}/\text{La}_{\text{PM}} = \sim 0.20 \pm 0.01$ ) and in the Pujili  
402 Granite ( $\text{Nb}/\text{La}_{\text{PM}} = 0.10$ ). Another major difference is the positive anomalies in Zr and Hf  
403 observed in the Pascuales tonalites and LO dacites ( $\text{Zr}/\text{Sm}_{\text{PM}} = 1.3\text{--}1.5$  and  $1.5\text{--}2.8$ ,  
404 respectively) versus negative Zr and Hf anomalies in Rio Cala andesites and dacites ( $\text{Zr}/\text{Sm}_{\text{PM}}$   
405  $= \sim 0.8 \pm 0.2$ ) and in Pujili Granite ( $\text{Zr}/\text{Sm}_{\text{PM}} \sim 0.4$ ). In the trondhjemites, Zr and Hf spikes are  
406 more pronounced ( $\text{Zr}/\text{Sm}_{\text{PM}} = 2.2\text{--}3.8$ ) than in the tonalites, the trondhjemitic sample GD002  
407 having the highest ratio. Plots of REE, Th, Y and Zr against Nb, a highly incompatible trace  
408 element and the least mobile during hydrothermal and/or seawater alterations (Pearce, 2014),  
409 show that Pascuales and LO volcanic rocks define trends with slopes intermediate between  
410 those of the island arc lavas and the OPB (Fig. S2).

411 In summary, the Pascuales felsic intrusions have tonalitic and trondhjemitic  
412 compositions, characterized by extremely low  $\text{K}_2\text{O}$ ,  $\text{TiO}_2$ ,  $\text{P}_2\text{O}_5$  and REE concentrations; they  
413 are moderately depleted in Nb relative to La and enriched in Zr and Hf relative to Sm. These  
414 chemical features clearly distinguish the Pascuales felsic compositions from the silicic  
415 volcanic rocks of the Rio Cala Arc, but are shared by the LO dacitic samples.

416

417 *6.2. Mafic rocks*

418

419 LOI vary from 1.6 wt% in CP605 through 2.2 wt% in CP607 to 3.9 wt% in GD004  
420 (Table 1). On an anhydrous basis, all samples have basaltic compositions ( $\text{SiO}_2 = 50.8\text{--}51.7$   
421 wt%,  $\text{MgO} > 5$  wt%). CP605 and CP607 have near primitive compositions ( $\text{MgO} = 7.4\text{--}8.1$   
422 wt%,  $\text{Cr} = 160\text{--}190$  ppm,  $\text{Ni} = 100\text{--}110$  ppm), whereas GD004 has a more differentiated  
423 composition, as shown by lower  $\text{MgO}$  (5.1 wt%),  $\text{Cr}$  (20 ppm) and  $\text{Ni}$  (40 ppm) contents and  
424 higher  $\text{TiO}_2$ , V and incompatible trace elements, such as REEs, Y, Nb, Th, Zr and Hf (Table  
425 1).

426 In the Harker diagrams (Figs. 7 and 8) the three analyzed basaltic samples fall  
427 systematically within the compositional fields of the Ecuadorian OPB and, in particular, their  
428 compositions are similar to those of the Piñón basalts previously sampled in the CCH  
429 (Reynaud et al., 1999; van Melle et al., 2008). Plotted against Nb, the concentrations in  
430 alteration-mobile incompatible elements (Sr, Rb and Ba) also are within the ranges of the  
431 variably altered Ecuadorian OPB (Fig. S2). In contrast, U concentrations in CP605, and to a  
432 lesser extent in CP607, plot above the Ecuadorian OPB trend, suggesting U gain during  
433 alteration.

434 On a chondrite-normalized REE diagram (Fig. 9D), samples CP605 and CP607 plot in  
435 the middle of the Ecuadorian OPB field at  $\text{Yb}_{\text{CN}} = \sim 16$ , whereas GD004 plots at  $\text{Yb}_{\text{CN}} = \sim 29$   
436 at the upper boundary among the most evolved OPB compositions. Samples CP605 and  
437 GD004 display flat REE patterns ( $\text{La}/\text{Yb}_{\text{CN}} = \sim 0.9$ ), while CP607 is slightly depleted in LREE  
438 ( $\text{La}/\text{Yb}_{\text{CN}} = \sim 0.6$ ). Samples CP607 and GD004 exhibit small negative anomalies in Eu  
439 ( $\text{Eu}/\text{Eu}^* = 0.87$  and  $0.93$ , respectively).

440 The Pascuales basaltic samples are significantly enriched in the most incompatible  
441 elements ( $\text{Nb} = 3.6\text{--}5.9$  ppm,  $\text{Th} = 0.36\text{--}0.45$  ppm) with respect to N-MORB (Fig. 9E). The  
442 values of  $(\text{Nb}/\text{La})_{\text{N-MORB}}$  (1.1–1.7) and  $(\text{Th}/\text{Nb})_{\text{N-MORB}}$  (1.5–2.1) are within the range of the

443 other Ecuadorian OPB (1.1–1.7 and 1.1–2.7, respectively) and within the range of the six  
444 CCH basalts previously published (1.1–1.4 and 1.2–1.9, respectively). Nb/U ratios (12–30) are  
445 lower than those in oceanic (49–50) and Ecuadorian (33–48) OPB, confirming U enrichment  
446 during alteration. Sample CP607 displays a strong positive anomaly in Sr ( $Sr/Sr^* = 2.2$ ),  
447 whereas CP605 shows a smaller positive anomaly ( $Sr/Sr^* = 1.3$ ), which are not correlated  
448 with higher  $Al_2O_3$  and Sr values and likely reflects alteration. In contrast, the slight Sr  
449 depletion in GD004 ( $Sr/Sr^* = 0.8$ ) is consistent with the small Eu anomaly, indicating minor  
450 plagioclase fractionation. In addition, Ti in GD004 is enriched relative to the adjacent REE,  
451 reflecting Fe-Ti oxide accumulation, in agreement with high  $Fe_2O_3$  contents and evolution  
452 toward ferrobasaltic composition.

453 In summary, the basaltic rocks collected in Pascuales are tholeiites with flat to slightly  
454 LREE depleted patterns, geochemically similar to the Late Cretaceous oceanic plateau basalts  
455 of the Piñón Fm. Samples CP605 and CP607 have moderately differentiated compositions,  
456 whereas GD004 have evolved toward a ferrobasalt, which is consistent with the mineralogy.  
457 Although they crop out within a very restricted area (Fig. 3), the three basalts exhibit highly  
458 variable Nb/La ratios (~1 to 1.56), suggesting that they represent different OPB units, a  
459 heterogeneity typically observed in CLIP basalts (Kerr et al., 2002b, 2003).

460

## 461 **7. Nd, Sr and Pb isotopic data**

462

463 The three basaltic samples, one tonalite (GD003) and two trondhjemites (CP604 and  
464 GD001) have been analyzed for Sr–Nd and Pb isotopic compositions. Results are reported in  
465 Table 1 and plotted in Fig. 10; complete results are listed in Table S4. The basalts of this  
466 study have homogeneous  $\epsilon Nd_i$  (+6.9 to +7.4) similar to two (out of three) previously

467 published basalts from the CCH and overlap the Nd–Sr isotopic fields of the CLIP and Late  
468 Cretaceous island arc volcanic rocks from Ecuador (Fig. 10A). Relatively high ( $^{87}\text{Sr}/^{86}\text{Sr}$ )<sub>i</sub>  
469 ratios (0.70464–0.70472) are likely related to the seawater and hydrothermal alterations  
470 observed in thin sections. Nevertheless, the range of the Sr isotopic ratios for all samples is  
471 rather restricted, precluding any major alteration-induced modifications on the Sr isotopic  
472 system. The ( $^{206}\text{Pb}/^{204}\text{Pb}$ )<sub>i</sub> and ( $^{207}\text{Pb}/^{204}\text{Pb}$ )<sub>i</sub> values of the Pascuales basalts are high and  
473 slightly scattered (18.64–18.93 and 15.54–15.63, respectively) but still in the range of the  
474 Ecuadorian OPB with the exception of CP607 which has the lowest ( $^{206}\text{Pb}/^{204}\text{Pb}$ )<sub>i</sub> and the  
475 highest ( $^{207}\text{Pb}/^{204}\text{Pb}$ )<sub>i</sub> ratios (Fig. 10C). However, because of the very low values of their  
476 Nb/U ratios (12–29 versus  $47 \pm 10$  in oceanic mantle, Hofmann, 1988), Pb isotopic data of the  
477 Pascuales basalts may not be meaningful, rather reflecting post-magmatic addition of U. Lead  
478 is also known to be mobile during alteration (Hauff et al., 2000b); but, in this study, its  
479 mobility cannot be evaluated because the concentrations are below the detection limit (<5  
480 ppm). Pascuales felsic intrusions have relatively low  $\epsilon\text{Nd}_i$  (+4.4 to +5.6), nevertheless similar  
481 to that of the CCH Piñón basalt Ca1 (+4.5) analyzed by Reynaud et al. (1999) and within the  
482 range of Late Cretaceous picrites and alkali basalts from Tortugal in Costa Rica ( $\epsilon\text{Nd}_i = +6.9$   
483 to +4.2; Hauff et al., 2000a; Trela et al., 2017) and the Beata Ridge in the Caribbean Sea  
484 ( $\epsilon\text{Nd}_i = +5.2$ –+5.4; Hauff et al., 2000b) and also similar to some gabbro–wehrlite cumulate  
485 samples from the San Juan Unit (Mamberti et al., 2004; Lapierre et al., 2010). In the diagram  
486 ( $^{143}\text{Nd}/^{144}\text{Nd}$ )<sub>i</sub> versus ( $^{206}\text{Pb}/^{204}\text{Pb}$ )<sub>i</sub> Pascuales felsic rocks fall in the same field as Tortugal  
487 lavas, which is subparallel to that of the Galapagos (Fig. 10B). The tonalite GD003 and the  
488 trondhjemite GD001, collected in the same outcrop (Fig. 3B), are similarly radiogenically  
489 enriched in ( $^{206}\text{Pb}/^{204}\text{Pb}$ )<sub>i</sub> and ( $^{207}\text{Pb}/^{204}\text{Pb}$ )<sub>i</sub> with respect to the tonalite CP603 which was  
490 sampled in a nearby outcrop (Fig. 3C) suggesting post-magmatic, small-scale variations. The  
491 more radiogenic Pb isotopes in GD001 and GD003 may reflect assimilation of minor amounts

492 of sediment which were interbedded in the basaltic crust. Small variations among the three  
493 felsic rocks also affect the Sr isotopic ratios, likely in relation with late-stage hydrothermal  
494 fluids.

495 In summary, the isotopic values for both Pascuales basaltic and felsic rocks are within  
496 the range of Ecuadorian OPB and volcanic rocks of other parts of the Caribbean oceanic  
497 plateau. However, with  $\epsilon\text{Nd}_i$  ranging between +4.4 and +5.6 the felsic plutonic rocks plot  
498 among the less radiogenic Nd compositions and have more radiogenic Sr and Pb  
499 compositions, different from those in the host basalts, but very close to those a Piñón basalt  
500 sampled in Guayaquil area. Homogeneous Nd isotopic ratios are consistent with derivation of  
501 the three felsic rocks from a common source, but very limited, small-scale variability in Sr  
502 and Pb isotopic composition suggests additional crustal assimilation and/or hydrothermal  
503 alteration.

504

## 505 **8. Discussion**

506

507 *8.1 Spatial, temporal and geochemical relationships between Pascuales felsic rocks and Las*  
508 *Orquideas volcanic rocks*

509

510 Both the Pascuales and LO magmatic rocks crop out in the same region of the CCH  
511 west of Guayaquil. On one hand, Pascuales tonalites and trondhjemites are intrusive within  
512 basalts that are similar to oceanic plateau basalts of the Piñón Fm. forming the basement of  
513 the CCH (Fig. 3) in terms of major elements, trace elements, and isotopes. On the other hand,  
514 LO dacites were sampled in Rio La Derecha and Rio Guaraguau located 30-40 km west from  
515 Pascuales, where they conformably overlay the top of the Piñón basalts (van Melle et al.,

516 2008). The LO volcanic rocks are interbedded with limestones that contain pelagic  
517 microfauna indicating a Coniacian age (Ordoñez, 2007; van Melle et al., 2008; Velasco and  
518 Mendoza, 2003), i.e. corresponding to an age of ~88 Ma according to the time scale of  
519 Gradstein et al. (2004). This age is consistent with the radiometric ages of 87–89 Ma obtained  
520 here and interpreted as the time of crystallization of the plutonic felsic rocks, indicating that  
521 the plutonic and volcanic events were coeval, or at least penecontemporaneous.

522 In addition to be closely spatially and temporally related both rock types share peculiar  
523 geochemical characteristics that clearly distinguish them from Cretaceous Ecuadorian arc-  
524 related volcanic rocks. Indeed, despite some scatter in  $K_2O$ , Ba, Sr (due to the mobility of  
525 these elements during alteration) and in  $Al_2O_3$ ,  $Na_2O$  and  $MgO$  (ascribed to variable  
526 abundances of plagioclase  $\pm$  pyroxene phenocrysts in the LO volcanic rocks, van Melle et al.,  
527 2008; Reynaud et al., 1999), Harker diagrams (Figs. 7 and 8) and plots of REE, Th, Zr and Y  
528 versus Nb (Fig. S2) show that the two Pascuales tonalites and the four LO dacites (~63–70  
529 wt.%  $SiO_2$ ) plot in the same compositional fields. The trondhjemitic samples extend these  
530 fields toward high-silica rhyolitic compositions despite the gap between ~70 and ~78 wt.%  
531  $SiO_2$ . All these rocks share the same low concentrations in incompatible minor elements (Ti,  
532 K, P) and extreme depletions in REE and Y (excepted one LO dacite enriched in K), that  
533 distinguish them from the Rio Cala Arc dacites. Very low  $K_2O$ ,  $TiO_2$ , HREE and Y  
534 concentrations also characterize the Pujilí Granite, but the latter is characterized by much  
535 higher La (40.2 ppm versus 3.7–5.0 ppm in Pascuales tonalites) and lower Yb (0.2 ppm  
536 versus 0.7 ppm in Pascuales tonalites) concentrations, yielding strongly fractionated  
537 normalized REE patterns ( $La/Yb_{CN} = 32$  in Pujili Granite versus 3.6–4.7 in Pascuales  
538 tonalites; Fig. 9A) indicative of residual garnet in the source of the Pujili Granite (Vallejo,  
539 2007) but not in that of the Pascuales tonalites. As a whole, major element compositions of  
540 Pascuales and LO felsic rocks form linear trends of decreasing  $MgO$ ,  $Fe_2O_3$ ,  $CaO$ ,  $Al_2O_3$ ,

541  $P_2O_5$  and Sr, and increasing  $Na_2O$ , La, Nb, Th and Zr with increasing  $SiO_2$  (Figs 7 and 8).  
542 Excluding the two LO andesitic/dacitic samples more enriched in MgO, the Pascuales felsic  
543 rocks and the three LO MgO-poor dacites these trends appear to be consistent with fractional  
544 crystallization of plagioclase, amphibole  $\pm$  pyroxene and apatite, as generally observed in the  
545 latest stages of differentiation of calc-alkaline magmatic series. From the tonalites to the  
546 trondhjemites, La/Yb<sub>CN</sub> values slightly increase from 3.6–4.7 to 4.4–6.5. The latter also have  
547 lower concentrations in Y, HREE and MREE (Y and Sm vs.  $SiO_2$  in Fig. 8), with concomitant  
548 decrease in (Sm/Yb)<sub>PM</sub> from 2.4 in the tonalites to 1.6 in the trondhjemites, whereas  
549 (Zr/Sm)<sub>PM</sub> increase from 1.3–1.5 in the tonalites to 2.2–3.8 in the trondhjemites. These  
550 features are interpreted as reflecting an increased control of the amphibole on the silica-richer  
551 liquid during magmatic differentiation (e.g., Davidson et al., 2007; Brophy, 2008; Dessimoz  
552 et al., 2012; Nandedkar et al., 2016; see section 8.2 for more details). The sample GD002 has  
553 the highest silica content and exhibits the strongest amphibole signature (Fig. 9B, C). This  
554 sample also displays a positive Eu anomaly, whereas the other two samples show no Eu  
555 anomalies. A positive Eu anomaly is generally thought to reflect plagioclase accumulation,  
556 but enrichment/depletion of Eu with respect to adjacent REE also result from competition  
557 between amphibole and plagioclase during fractionation (Tarney et al., 1979; Dessimoz et al.,  
558 2012) as suggested by higher Sr/Y ratios in the tonalites (Sr/Y = 31–32) with respect to the  
559 trondhjemites (Sr/Y = 9–16).

560 Cogenetic relationships are supported for the tonalites and trondhjemites which share  
561 similar  $^{143}Nd/^{144}Nd$  ratios. However, the two LO MgO-rich samples (EQ94.1 and EQ94.2)  
562 analyzed by Reynaud et al. (1999) cannot have the same source composition as the Pascuales  
563 felsic rocks because they exhibit  $\epsilon Nd_i$  values (+6.02 and +7.14, respectively) significantly  
564 higher than those of Pascuales tonalites and trondhjemites (+4.41 to +5.59). These two LO  
565 lavas contain Mg-rich pyroxene phenocrysts (Reynaud et al., 1999) and could be explained by



566 mixing between a felsic melt and a mafic (liquid or solid) component, as suggested by the  
567 decrease of the  $\epsilon\text{Nd}_i$  values with increasing  $\text{SiO}_2$  and Nb contents (Fig. 11) and the linear  
568 compositional trend in the  $\text{MgO-SiO}_2$  binary diagram (Fig. 7). No isotopic data are available  
569 for the other LO dacites and they are not directly associated on the field, therefore, they might  
570 not be genetically related to Pascuales felsic rocks and might also plot on the same mixing  
571 trends. Nevertheless, because both rock types share the same geochemical features and  
572 display subparallel, similarly fractionated trace element patterns (Fig. 9), it is assumed that a  
573 derivation from magmas having close compositions and/or that evolved via similar magmatic  
574 processes took place.

575           Our new geochemical and chronological data together with previous regional  
576 models allow to propose that: (i) the Pascuales tonalites can be considered as plutonic  
577 equivalents of the LO dacites, representing a same magmatic episode; (ii) this magmatic  
578 episode is middle-Coniacian, based on zircon dating of Pascuales intrusives, in agreement  
579 with microfauna contained in LO sediments; (iii) the LO volcanites rest directly on the top of  
580 the Piñón basalts, yielding a minimum late Turonian – early Coniacian age (~88–90 Ma) for  
581 the basaltic exposure in this area (Luzieux et al., 2006; Ordoñez et al., 2006; van Melle et al.,  
582 2008). LO volcanites and associated sediments are overlain by a thick pile of sediments of the  
583 Calentura and Cayo Fms. dated, respectively, late-Coniacian to middle-Campanian, and  
584 middle-late-Campanian (van Melle et al., 2008; Ordoñez et al., 2006). According to van Melle  
585 et al. (2008) increasing abundance of volcanoclastic deposits and debris flows in the middle to  
586 upper part of the Calentura Fm. suggests the onset of an instability period announcing the  
587 construction of the San Lorenzo island arc. This arc was active from mid-Campanian to early-  
588 middle Maastrichtian (~80–70 Ma) and was the source of the Cayo back-arc volcanoclastic  
589 deposits. The short-lived Pascuales - LO magmatic episode exhibits atypical calc-alkaline  
590 affinity and took place in the time interval (~90–80 Ma) that followed the final stage of

591 building of the oceanic plateau in coastal Ecuador and preceded self-sustained subduction  
592 zone beneath the San Lorenzo island arc. The possibility that this atypical magmatism was  
593 related to initiation of the Late Cretaceous subduction at the leading edge of the CLIP will be  
594 discussed section 8.3.2. Interestingly, the LO Member is intruded by dolerites (samples  
595 04LD01 and 04GW-01 analyzed by Allibon et al., 2008) that display major, trace element and  
596 lead and neodymium isotopic compositions within the range of the San Lorenzo and Rio Cala  
597 tholeiitic basalts and basaltic andesites (Figs. 7 and 8); according to Luzieux (2007) these  
598 intrusives would be coeval or younger than the Calentura Fm. and related to the San Lorenzo  
599 arc.

600

## 601 *8.2 Geochemical constraints on the petrogenesis of Pascuales and Las Orquideas felsic rocks*

602

603 Small bodies of tonalites and trondhjemites (also referred as oceanic plagiogranites,  
604 Coleman and Donato, 1979, see Koepke et al., 2007 for a review) and volcanic equivalents  
605 are relatively common in thickened oceanic crust in all types of oceanic settings (mid-oceanic  
606 ridges; back-arc spreading centers; plume-related plateau basalts; subduction zones) and in  
607 ophiolites. Based on inferences from field relationships, trace element geochemistry and  
608 isotope compositions, they are believed to represent products of either differentiated basaltic  
609 magmas (e.g., Lippard et al., 1986; Amri et al., 1996; Floyd et al., 1998; Selbekk et al., 1998;  
610 Rao et al., 2004; Bonev and Stampfli, 2009; Rollinson, 2009; Haase et al., 2016), or partial  
611 melting of hydrated basalts, gabbros or sheeted dikes (e.g., Gerlach et al., 1981; Pedersen and  
612 Malpas, 1984; Flagler and Spray, 1991; Floyd et al., 1998; Selbekk et al., 1998; Gillis and  
613 Coogan, 2002; Koepke et al., 2007; Brophy, 2009; Rollinson, 2009; Brophy and Pu, 2012;

614 Tsuchiya et al., 2013; France et al., 2014), or both fractional crystallization and partial  
615 melting of hydrated mafic rocks (Wanless et al., 2010).

616 Pascuales tonalites and LO dacites overlap in terms of most major elements with calc-  
617 alkaline, silica-rich (63–75 wt.% SiO<sub>2</sub>) experimental melts produced by crystal differentiation  
618 of hydrated tholeiitic basaltic and andesitic magmas, as well as those produced by dehydration  
619 melting of amphibolite and hydrous partial melting of basalt and gabbro, under varying  
620 conditions of pressure, water content and oxygen fugacity (e.g., Dixon-Spulber and  
621 Rutherford, 1983; Koepke et al., 2004; Berndt et al., 2005; Sisson et Kelemen, 2005; France  
622 et al., 2010, 2014; Blatter et al., 2013; Nandedkar et al., 2014; Müntener and Ulmer, 2018,  
623 among other; Fig. S3). Considering FeO\*/MgO ratios and incompatible minor elements; the  
624 Fig. 12 shows that Pascuales tonalites and LO dacites have the lowest FeO\*/MgO ratios and  
625 K<sub>2</sub>O, TiO<sub>2</sub>, P<sub>2</sub>O<sub>5</sub> concentrations at given SiO<sub>2</sub> and MgO contents. Such low FeO\*/MgO ratios  
626 and extreme depletion in TiO<sub>2</sub> in dacitic compositions exclude an origin by fractional  
627 crystallization of anhydrous tholeiites (e.g., Dixon-Spulber and Rutherford, 1983; Berndt et  
628 al., 2005), and thus an origin of Pascuales tonalites and LO dacites by differentiation of Piñón  
629 basaltic magmas. Instead they argue for a magmatic evolution under high water contents  
630 and/or high oxidizing conditions. Low to very low K, Ti and P concentrations in experimental  
631 dacites and rhyodacites and natural plutonic equivalents have been interpreted mainly as  
632 reflecting depletions in the parent basalt (Dixon-Spulber and Rutherford, 1983; Beard and  
633 Lofgren, 1991; Koepke et al., 2004; Berndt et al., 2005). Alternatively, water-saturated partial  
634 melting of mafic rocks yields silicic melts with low FeO\*/MgO and TiO<sub>2</sub> contents explained  
635 by crystallization of Fe-Ti oxides (Beard and Lofgren, 1991), whereas low P<sub>2</sub>O<sub>5</sub> contents may  
636 reflect the presence of residual apatite in the solid residues (Wanless et al., 2010). For Koepke  
637 et al. (2004, 2007), extreme depletion in TiO<sub>2</sub> contents in intermediate and silicic partial melts  
638 reflects a refractory protolith and is a key parameter to discriminate between plagiogranite

639 generated by anatexis of hydrothermally altered cumulate gabbro from plagiogranite formed  
640 by differentiation of basaltic magmas in the oceanic crust.

641         The anomalously low REE contents of the Pascuales tonalites and LO dacites with  
642 respect to common calc-alkaline silicic rocks imply additional constraints. Amphibole is an  
643 important hydrous phase that accommodates higher amounts of REE and other highly  
644 incompatible elements than other major anhydrous phases (i.e., olivine, pyroxenes,  
645 plagioclase) during the evolution of water-rich magmas. Because its stability increases with  
646 increasing amount of water in the magma and with increasing pressure (Grove et al., 2003;  
647 Barclay and Carmichael, 2004), its crystallization in water-rich, arc magmas in the lower crust  
648 has for effects to dramatically reduce the REE increase rate and significantly modify  
649 incompatible trace element ratios in the derivative melts (Davidson et al., 2007; Rodriguez et  
650 al., 2007; Brophy, 2008; Rollinson, 2009; France et al., 2014; Nandedkar et al., 2016).  
651 Similarly, amphibole, either as a residual phase (dehydration melting of amphibolite) or as a  
652 reacting phase (hydrous partial melting), exerts a control over the REE in the low-degree,  
653 silica-rich, partial melts from mafic rocks, because their incompatibility continuously  
654 decreases with increasing liquid SiO<sub>2</sub> contents, eventually shifting from incompatible to  
655 compatible (e.g., Sisson, 1994; Klein et al., 1997; Dalpe and Baker, 2000; Nandedkar et al.,  
656 2016). Experimentally-based numerical models have explored the REE behaviors, absolute  
657 abundances and degrees of enrichment (or enrichment factor F) in felsic magmas (~63–76  
658 wt.% SiO<sub>2</sub>) relative to the initial rock source or parent basalt for various compositions and  
659 different depths and mechanisms of differentiation. They show that REE concentrations in  
660 residual liquids slowly increase (F ~1.2–1.4, Brophy, 2008) or remain nearly constant (F ~0.5,  
661 Rodriguez et al., 2007; F ~0.9, Nandedkar et al., 2016) over the entire range of differentiation  
662 of arc magmas if amphibole is a major early fractionating phase at lower crustal pressures ( $\geq$   
663 0.7 GPa, Alonzo-Perez et al., 2008; Blatter et al., 2013; Ulmer et al., 2018). Assuming that

664 Pascuales and LO dacitic magmas were generated after removal of ~50% of an amphibole-  
665 rich assemblage from a water-rich arc magma, such low enrichment factors would require less  
666 than ~2.8–4.2 ppm of La and less than ~0.4–0.6 ppm of Yb in the parent basaltic magmas,  
667 well below the REE contents of the more primitive Rio Cala basalts (Fig. 8) and other  
668 common arc basalts, suggesting derivation from water-rich, highly depleted magmas. In  
669 partial melting scenarios, enrichment factors calculated by Brophy (2008) vary between 2.1  
670 and 3.2 for La and between 0.4 and 2.3 for Yb in derivative partial melts for a similar 63–70  
671 wt.% SiO<sub>2</sub> range, regardless the type (equilibrium, fractional, accumulated fractional) and  
672 mechanism (dehydration or hydration melting) of melting and compositions of the protolith.  
673 Application to Pascuales and LO dacitic rocks suggests strongly depleted rock sources  
674 containing 1.0–2.5 ppm of La and 0.3–1.8 ppm of Yb, more compatible with mafic–  
675 ultramafic cumulate protoliths rather than basaltic protoliths that solidified from slightly to  
676 moderately differentiated melts (see Fig. 12, France et al., 2014's experimental melting of  
677 MORB dykes).

678 Pascuales and LO felsics exhibit negative Nb anomalies in PM-normalized diagrams, a  
679 feature commonly attributed to an emplacement above a subduction zone. However, negative  
680 Nb anomalies is not always symptomatic of subduction settings as they are observed in  
681 Iceland and MOR dacites believed to be produced by low degrees of partial melting of  
682 hydrated oceanic crust (Gunnarsson et al., 1998; Haase et al., 2005; Wanless et al., 2010;  
683 Wilbold et al., 2009). Niobium is only moderately incompatible in amphibole equilibrated  
684 with silica-rich, calc-alkaline melts, with  $D_{\text{Nb/La}}$  values above the unity, resulting in lower  
685  $(\text{Nb/La})_{\text{PM}}$  in the felsic melts (Foley et al., 2002; Haase et al., 2005; Münker et al., 2004). In  
686 addition, Nb concentrations in melt are also controlled by magnetite and ilmenite as stable  
687 phases in the restite. The extremely low REE concentrations observed in Pascuales felsic  
688 rocks and LO dacites also explain the Zr and Hf positive anomalies on the PM-normalized

689 multi-element patterns, which are not observed in common tonalites and dacites. Like the  
690 REE, HFSE become more compatible in amphibole with increasing silica contents in melts  
691 (e.g., Foley et al., 2002; Nandedkar et al., 2016), but REE compatibility increases faster than  
692 HFSE compatibilities, while MREE are preferentially incorporated over LREE and HREE. As  
693 a result, Zr/Sm ratios increase with increasing silica contents in H<sub>2</sub>O-rich liquids (Davidson,  
694 2007; Nandedkar et al., 2016; Wanless et al., 2010).

695 In conclusion, major and trace element data (i.e., low FeO\*/MgO, very low Ti and  
696 REE contents, high Zr/Sm ratios) suggest that the formation of Pascuales and LO felsic rocks  
697 result from magmatic processes largely dominated by amphibole and Fe-Ti oxides, implying  
698 evolution at high water contents. This conclusion is also consistent with the explosive  
699 emplacement of the LO dacites (van Melle et al., 2008). These conditions can be fulfilled by  
700 two magmatic processes, hydrous partial melting of mafic-ultramafic material or high-  
701 pressure, fractional crystallization of water-rich, arc-related magmas (or by a combination of  
702 both processes). Both models require fluxing of hydrous fluids in the crustal protoliths or in  
703 the mantle sources. However, amphibole alone cannot explain the REE extreme depletion;  
704 unusually depleted compositions of the protoliths or parent magmas are also needed.

705

### 706 *8.3 Geodynamic implications*

#### 707 *8.3.1 The partial melting of mafic cumulates evidence*

708 Several aspects support a model invoking partial melting of mafic cumulates to  
709 generate Pascuales dacitic magma(s): 1) The Pascuales plutonic bodies are intrusive within  
710 basalts that unambiguously belong to the Piñón OPB, and both formations are almost  
711 contemporaneous, which implies that the OPB were still hot during the emplacement of the  
712 plutons. If, in addition, water was provided, the temperature needed for generating dacitic

713 melts from a gabbroic protolith ( $< 1000^{\circ}\text{C}$ ; e.g. Koepke et al., 2004, 2005) could have been  
714 reached. 2) Natural examples in modern tectonic settings, experimental work and modelling  
715 demonstrated that hydrous re-melting of mafic rocks yields K-poor calc-alkaline, rhyodacitic  
716 magmas characterized by arc-like features such as negative Nb anomalies, independantly of  
717 the origin of the protholith (N- and E-MORB-types or island-arc tholeiites) and of the tectonic  
718 setting where partial melting took place (e.g. Haase et al., 2005; Wanless et al., 2010;  
719 Willbold et al., 2009). In addition, other features such as the positive Zr anomalies and low  
720 REE contents that distinguish the Pascuales felsics from common subduction-related dacites  
721 are also characteristics of hydrous partial melts from mafic rocks.

722         The isotopic data exclude a common source for the Pascuales basalts and felsics.  
723 However, a Piñón basalt sampled in the CCH (Ca1 in Fig. 10) exhibits a less radiogenic initial  
724  $^{143}\text{Nd}/^{144}\text{Nd}$  composition ( $\epsilon\text{Nd}_i = +4.49$ ), slightly lower than those characterizing the tonalite  
725 and trondhjemites, and plots below the fields of the CLIP and Galapagos Plume at 90 Ma  
726 (Fig. 10A, B). Although this composition is unique among the six basalts analyzed in the  
727 CCH (and among other Ecuadorian OPB), a few picrites and alkali basalts belonging to the  
728 ~90–89 Ma oceanic plateau in Tortugal (Costa Rica; Hauff et al., 2000a; Trela et al., 2017)  
729 and in the Beata Ridge (Caribbean Sea; Dürkefälden et al., 2019; Hauff et al., 2000a) have  
730  $\epsilon\text{Nd}_i$  values (down to +4.24 and +5.41, respectively) lower than those of the basalts from the  
731 Galapagos Plume. Indeed, the three Pascuales felsic rocks plot in a field defined by the  
732 Tortugal magmatic rocks in the initial ( $^{143}\text{Nd}/^{144}\text{Nd}$ ) versus ( $^{206}\text{Pb}/^{204}\text{Pb}$ ) diagram (Fig. 10B),  
733 suggesting that their protoliths could have derived from a mantle source region more enriched  
734 than those of the main CLIP magmatic rocks. This mantle source region would be a mixture  
735 of more radiogenic Nd and less radiogenic Pb isotopic compositions than common CLIP  
736 rocks, and less radiogenic Nd and more radiogenic Pb isotopic compositions such as those  
737 characterizing the Tortugal picrites and alkali basalts.

738 In the Ecuadorian Western Cordillera, early to late Cretaceous ultramafic and mafic  
739 rocks believed to represent lower crust fragments of the Pallantaga oceanic plateau such as the  
740 San Juan cumulates (Hughes and Pilatasig, 2002; Jaillard et al., 2009; Lapierre et al., 2000;  
741 Mamberti et al., 2004) and the Tortoras mafic granulites and amphibolites (Amortegui et al.,  
742 2011; Beaudon et al., 2005) (Fig. 2) also have the low REE and Ti compositions required to  
743 represent the protoliths of the Pascuales felsic magma. Nd-Sr-Pb isotopic data for these two  
744 terranes are shown in Fig. S4. The San Juan Unit exposes peridotites, layered werhlites, and  
745 layered and isotropic gabbros that yield a Sm/Nd isochron of  $123 \pm 13$  Ma (Lapierre et al.  
746 2000) and a zircon U/Pb age of  $87.1 \pm 1.6$  Ma (Vallejo et al., 2006) and shows variable  
747 geochemical and isotopic compositions (Mamberti et al., 2004; Fig. S4A), indicating  
748 intercalation of two distinct magmatic sequences, possibly representing intrusions of a  
749 younger, Late Cretaceous, oceanic plateau magmas in an older, Early Cretaceous, oceanic  
750 plateau (Jaillard et al., 2009; Mamberti et al., 2004; Spikings et al., 2015; Vallejo et al., 2009).  
751 Values of  $\epsilon\text{Nd}_i$  in San Juan cumulates range from +8.1 to +2.5 overlapping those of the Piñón  
752 OPB and Pascuales mafic and felsic rocks, but their  $(^{206}\text{Pb}/^{204}\text{Pb})_i$  ratios are significantly lower  
753 ( $< 18.5$ ; overlapping the picrites from the Guaranda terrane of the Pallatanga Unit; Mambeti  
754 et al., 2003), which precludes involvement of cumulates with similar isotopic compositions as  
755 protoliths of the Pascuales dacitic magma. The Tortoras granulite and amphibolites also span  
756 a wide range of  $(^{143}\text{Nd}/^{144}\text{Nd})_i$  ( $\epsilon\text{Nd}_i$  values ranging from +7.9 to + 1.8) but display more  
757 radiogenic Sr and Pb isotopic compositions. The range of  $(^{206}\text{Pb}/^{204}\text{Pb})_i$  (18.72–19.07) is quite  
758 restricted and, in the initial  $(^{143}\text{Nd}/^{144}\text{Nd})$  versus  $(^{206}\text{Pb}/^{204}\text{Pb})$  diagram (Fig. S4B), their  
759 compositions overlap with those of Pascuales rocks. The amphibolites that have the lowest  
760  $(^{143}\text{Nd}/^{144}\text{Nd})_i$  ratios are those that have the highest  $(^{207}\text{Pb}/^{204}\text{Pb})_i$  ratios (Fig. S4C) and  
761  $(^{208}\text{Pb}/^{204}\text{Pb})_i$  (not shown), which is consistent with mixing with pelagic sediment. Such  
762 enrichments in radiogenic Pb likely occurred during the deformation and amphibolitisation of



763 the former basalts and cumulates. In contrast, isotopic compositions of the amphibolites the  
764 least enriched in radiogenic Pb plot with the Pascuales felsic rocks in the Nd–Pb isotopic  
765 spaces overlapping, or not far from, the OPB, Tortugal and Galapagos fields (Figs. S4 B, C),  
766 indicating restricted or no contribution of sediment. Chemical and isotopic compositions of  
767 Tortoras metamorphic cumulates thus compared well with the compositions expected for the  
768 protoliths of Pascuales dacitic magma. However, low radiogenic Nd composition of the  
769 trondhjemite CP603 is not correlated with higher values of  $(^{207}\text{Pb}/^{204}\text{Pb})_i$  and  $(^{208}\text{Pb}/^{204}\text{Pb})_i$   
770 ratios, suggesting that its lower  $(^{143}\text{Nd}/^{144}\text{Nd})_i$  ratio may be a primary feature of the mantle  
771 source region. The slight enrichments in radiogenic Pb observed in the samples GD001 and  
772 GD003 with respect to CP603 indicate very small-scale variations likely reflecting post-  
773 magmatic contamination.

774 High temperature metamorphism and granulite formation are commonly associated  
775 with partial melting of the protolith. The metamorphism of the Tortoras rocks was dated  
776 around 85 Ma in hornblende, a cooling age that post-dated the peak metamorphism (Vallejo et  
777 al., 2006, 2009), which is also the age of the Pujili Granite (Vallejo et al., 2009). The granulite  
778 and amphibolites experienced peak metamorphic conditions of 800°–850°C in the plagioclase  
779 stability field (<6–9 kbar; Beaudon et al., 2005) and they include metamorphic mantle  
780 peridotite in addition to metacumulate (Amortegui et al., 2011), therefore regional  
781 metamorphism likely occurred at the crust – lithospheric mantle boundary, at the base of a  
782 20–25 km thick oceanic crust consistent with the estimate thickness for the Caribbean plateau  
783 crust (Mauffret and Leroy, 1997). It is reasonable to believe that similar lithologies  
784 undergoing similar processes were also present at the base of the Piñón Fm. in the CCH,  
785 providing possible sources for the Pascuales and LO felsic magmas (see also the deep crustal  
786 xenolith suites in SW Colombia for similar lithologies, Weber et al., 2002). Further evidence  
787 may be represented by the Piñón amphibole-bearing gabbros that yielded a cooling age of ca.

788 89 Ma (Luzieux et al., 2006) and which are now exposed ~20 km north of the Pascuales area.  
789 Indeed, the crystallization history of this gabbro may have coincided with melting of Piñón  
790 cumulates, and thus with the generation of the Pascuales and LO felsic magmas.  
791 Unfortunately, no detailed petrographic and geochemical data were published for these  
792 hornblende-bearing gabbros, so they may be interpreted as either a residual material of partial  
793 melting or as cumulates of arc magma differentiation, both types being almost  
794 petrographically indistinguishable (Ulmer et al., 2018).

795 In summary, major, trace and isotopic compositions are compatible with an origin of  
796 the Pascuales felsics by partial melting of mafic cumulates assumed to be present in the lower  
797 crust of the Piñón Fm. and possibly belonging to an older plume-related magmatic pulse or  
798 event. The protoliths might have derived from a mantle source region characterized by lower  
799 radiogenic Nd and more radiogenic Pb isotopic compositions than the common CLIP rocks.  
800 Alternatively, the low Nd radiogenic signature could result from addition of a small amount  
801 of pelagic sediments. It is assumed then that partial melting must have occurred in a hot and  
802 dynamic environment associated with deformation, hydration and metamorphism of mafic-  
803 ultramafic protholiths in deep-seated shear zones.

804

### 805 *8.3.2 Felsic intrusions: a subduction initiation signature?*

806 In several places in the Northwestern Andes and the Caribbean, the CLIP is intruded  
807 by gabbroic plutons and tonalitic batholiths with arc-like affinity signature; these plutons  
808 emplaced soon after the OPB extrusion and most of them are interpreted as crystallization from  
809 juvenile, silicic magmas recording the initiation of an oceanic arc on the top of the oceanic  
810 plateau. These places include Western Colombia (e.g. Altamira, Zapata-Villada et al., 2017;

811 Buga, Villagomez et al., 2011; Bolivar Ultramafic Complex and Vijes (rhyodacitic) Felsites,  
812 Kerr et al., 2004; Santa Fe and Burritica, Weber et al., 2015), Aruba (van de Lelij et al., 2010;  
813 White et al, 1999; Wright and Wyld, 2011), Curaçao (Kerr et al., 1996 and Wright and Wyld,  
814 2011); and Panama (Azuero Marginal Complex, Buchs et al, 2010). Some geochemical  
815 similarities and differences between these felsic intrusions and the Pascuales and LO felsic  
816 rocks are shown in Fig. S5. Compared to Pascuales tonalites, the Aruba, Santa Fe, Buritica  
817 and Buga tonalites have higher overall REE abundances, but still lower than the Rio Cala  
818 dacites, a difference that can be explained by refractory protholiths (gabbro cumulates) for  
819 Pascuales and more enriched protoliths (basalts) for the other rocks. With the exception of the  
820 Pujili Granite, all these rocks exhibit incompatible trace element contents and ratios indicating  
821 that garnet had played no or very minor role as a residual phase, thus suggesting magma  
822 generation at pressures lower than  $\sim 0.7$  GPa. Like for LO volcanic rocks, these late  
823 Cretaceous silicic intrusives have been interpreted as subduction-related based on calc-  
824 alkaline affinities and Nb-Ta negative anomalies on N-MORB and PM-normalized multi-  
825 element diagrams (see Whattam and Stern, 2015, for a review). However, as discussed in  
826 Sections 8.2 and 8.3.1, partial melting of hydrated mafic rocks produces similar melt  
827 compositions, and does not necessarily require plate subduction settings. In the other hand,  
828 these intrusions occurred less than 10 Ma before steady-state, west-dipping subduction zones  
829 beneath the San Lorenzo and Rio Cala intra-oceanic island arcs (see introductory section), a  
830 time lag predicted by plate-tectonic models for the initiation of self-sustained subduction  
831 zones (Stern and Gerya, 2018; Whattam and Stern, 2015). In this view, this silicic magmatism  
832 that occurred shortly after (or even slightly overlap in time; van de Lelij et al., 2010; Whattam  
833 and Stern, 2015) the eruption of the Piñón basalts can be interpreted as the earliest stage of  
834 intra-oceanic subduction associated with widespread extension and asthenospheric upwelling

835 leading to the emplacement of basaltic magmas weakly or not affected by subduction fluids  
836 (Stern and Gerya, 2018).

837         On the basis of the lithologies and tectono-magmatic-metamorphic events recorded in  
838 Tortoras terrane, we propose that the hottest, deeper parts of the CCH oceanic plateau in  
839 Guayaquil area underwent similar high-temperature shear deformation and metamorphism  
840 and remelting triggered by intrusion and crystallization of younger mafic magmas in response  
841 to regional extension and asthenospheric upwelling. This agrees with crustal thickness  
842 estimates from forward modelling of potential data (Feinguer and Seguin, 1983; Aizprua et  
843 al., 2020) which define a ~7 km thick crust at the center-east CCH (i.e. 8 km thinner than  
844 unaffected plateau settings in west Ecuador). Without further evidence this thinning is  
845 tentatively ascribed to the same Late Cretaceous extensional episode. The composition of the  
846 upwelling mantle remains unknown since no basaltic lavas overly the top of the Piñón Fm.  
847 and the Ecuadorian OPB show no subduction contribution in their chemical signature (e.g.  
848 Hastie et al., 2013 and references therein). These underplating basalts could be either plume-  
849 related or hybrid between plume and arc as proposed by Whattam and Stern (2015) or arc  
850 basalts. A significant latent question is to know whether the Pascuales felsic rocks were co-  
851 magmatic or not with gabbroic and dioritic intrusions, as suggested by Pichler and Aly (1983)  
852 and Benitez (1995). Unfortunately, these rocks have not been clearly identified in the area and  
853 therefore, they have never been studied, nor dated. The lack of ~87–89 Ma aged mafic plutons  
854 intruded into the plateau and clearly identified as subduction-related and the lack of bimodal  
855 volcanism in the LO Member make not possible to firmly assert that the Pascuales and LO  
856 silicic magmatism was related to initiation of the San Lorenzo arc. We cannot exclude local  
857 remelting of the oceanic plateau without subduction (i.e., gravitational instability, subsidence  
858 effects); examples of juvenile, K-poor, calc-alkaline, dacitic magmas are reported in the  
859 Iceland basaltic plateau (Wilbold et al., 2009). However, sedimentary recordings in the

860 Calentura Fm. (van Melle et al., 2008), the wealth of petrologic and geochronologic data and  
861 plate-tectonic models suggest that this region localized at the SW leading edge of the  
862 Caribbean plateau was subjected to tectonic instability during or just after the end of plume-  
863 related magmatism. Therefore, intrusions of new basaltic magmas during initiation of late  
864 Cretaceous subduction are presently the best explanation for the partial melting of the mafic  
865 rocks forming the Piñón Fm., as suggested for other tonalitic intrusions in the CLIP (e.g.,  
866 Wright and Wyld, 2011; Weber et al., 2015).

867

## 868 **9. Conclusions**

869

870 1) Several 'granitic-like' igneous bodies intruded within basalts and metabasalts of the  
871 Piñón Fm. (OPB part of the Caribbean Large Igneous Province, CLIP) in SW Ecuador near  
872 the town of Pascuales. Petrographic and mineralogical analyses allow defining these  
873 intrusions as tonalites and trondhjemites. Zircon U-Pb ages obtained by LA-ICP-MS yield ca.  
874 ~87-89 Ma for one tonalite and two trondhjemites. Trace elements, field and chronological  
875 data indicate that they are related to Las Orquideas dacitic breccias, which emplaced on the  
876 Piñón Fm. during the Coniacian.

877 2) Geochemical compositions of the Pascuales felsic rocks are calc-alkaline but differ  
878 from typical subduction-generated magmatic rocks by lower  $\text{FeO}^*/\text{MgO}$  ratios, extreme  
879 depletions in  $\text{TiO}_2$  and  $\text{P}_2\text{O}_5$ , low La/Yb and moderately elevated Sr/Y ratios. In addition, on  
880 primitive mantle-normalized multi-element diagrams, they are only moderately depleted in  
881 Nb relative to La and enriched in Zr relative to Sm. Similar compositions are reproduced by  
882 experiments and modeling of hydrous partial melting of mafic protoliths, and observed as  
883 intrusions in oceanic crust in orogenic and anorogenic tectonic settings. However Pascuales

884 felsic rocks are characterized by extreme depletions in REE and Y, which are not observed in  
885 other felsic intrusives of similar ages emplaced in the CLIP.

886 3) Isotope systematics (Nd-Sr-Pb) are robust for Nd and only marginally affected by  
887 alteration for Sr and Pb data for the felsic bodies. Their isotope compositions overlap with the  
888 field of the Caribbean oceanic plateau basalts, but plot at the least radiogenic Nd end-member  
889 compositions.

890 4) The wealth of geochemical and isotopical data are consistent with partial melting of  
891 hydrated OPB and can be accounted by a strong control of residual amphibole and Fe-Ti  
892 oxides during the formation of the magmas. In addition, geochemical modeling and nature  
893 analogues show that the extreme REE and Y concentrations require hydrous partial melting of  
894 refractory mafic cumulates rather than less depleted basaltic protoliths.

895 5) The geochemical, chronological and geodynamic context suggest that both the  
896 Pascuales and Las Orquideas felsic rocks represent silicic magmatism resulting from partial  
897 melting of the deeper crust of the oceanic plateau during the final stage of its building. The  
898 occurrence of this magmatism at the SW border of the CLIP, less than 10 Ma before the  
899 activity of the subduction zones beneath the San Lorenzo - Rio Cala intra-oceanic island arcs,  
900 suggests that the melting event may be related to the initiation of the subduction during Late  
901 Cretaceous.

902

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908

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## 1490 **Figure Captions**

1491 Fig. 1. (A) Plume-induced subduction initiation model of the Caribbean Large Igneous  
1492 Province (CLIP) between 89-85 Ma (modified from Whattam and Stern, 2014). Green areas  
1493 show supposed active arcs. (B) Geodynamic cartoon showing the configuration of central-  
1494 south Ecuador and north Peru. Abbreviations are as follows: AM, Amotapes massif; CCH,  
1495 Chongón-Colonche hills; JF, Jubones fault; NAP, North American plate; SAP, South  
1496 American plate; WC, Western Cordillera.

1497

1498 Fig. 2. (A) Geological map of the Western Cordillera and forearc areas of Ecuador (Eguez et  
1499 al., 2017). (B) Simplified geologic columns representative of western Ecuador. Abbreviations  
1500 are as follows: CCH, Chongón-Colonche Hills; MB, Manabí basin; PB, Progreso basin; PG,  
1501 Pujilí Granite; TA, Tortoras amphibolite; SJ, San Juan Unit; POPB, Pinon oceanic plateau  
1502 basal; WC, Western Cordillera.

1503

1504 Fig. 3. (A) Aerial view of the Pascuales area (Google Earth image) showing sample location  
1505 and the intrusive bodies (red polygons). (B, C) Field photographs of tonalitic and  
1506 trondhjemitic outcrops. (D) Field photography of the basalt GD004. The asterisk refers to  
1507 dated samples.

1508

1509 Fig. 4. Composition of clinopyroxenes and amphiboles from the studied Pascuales rocks. (A)  
1510 Pyroxenes from the metabasalts CP605 and GD004 in the Mg-Ca-Fe diagram of Morimoto et  
1511 al. (1998). (B) Variation of  $\text{Al}_2\text{O}_3$  (wt. %) vs. Mg# in CP605 and GD004 clinopyroxenes. (C)  
1512 Variation of Mg# vs. Si in amphiboles from the tonalite CP601 and the metabasalts CP605  
1513 and CP607. (D) Variations of  $(\text{Na} + \text{K})_{\text{A}}$  vs.  $\text{Al}^{\text{IV}}$  in amphiboles from the tonalite CP601 and  
1514 the metabasalts CP605 and CP607. In panels (C) and (D), relicts of aluminous amphiboles  
1515 preserved in late-stage magnesio-hornblendes are circled. Numbers of atoms per formula  
1516 unit (apfu) in amphiboles are calculated on the basis of 13 cations excluding Ca, Na, K.  
1517 Nomenclature of amphiboles from Leake et al. (1997). Sample locations are shown on Fig. 3.

1518

1519 Fig. 5. (A) Terra Wasserburg diagram for the tonalite CP024. (B) Terra Wasserburg diagram  
1520 for the tonalite CP601. (C) Terra Wasserburg diagram for the trondhjemitic CP603.

1521

1522 Fig. 6. Normative Ab-An-Or plots of the Pascuales felsic plutonic rocks (this study) along  
1523 with Las Orquideas volcanic rocks (data from Reynaud et al., 1999 and van Melle et al.,  
1524 2008). Fields are after Baker (1979): tonalites (To), trondhjemites (Tr), granodiorites (Gd)  
1525 and granites (Gr).

1526

1527 Fig.7. Harker diagrams showing major oxide variations against SiO<sub>2</sub> (wt.%) of the studied  
1528 Pascuales basaltic lavas and felsic plutonic rocks. Other late Cretaceous Ecuadorian magmatic  
1529 rocks are projected for comparison with the studied rocks; data are from: (1) Reynaud et al.  
1530 (1999), Kerr et al. (2002a), Mamberti et al. (2003), Vallejo (2007), Chiarada (2009), and  
1531 Allibon et al. (2008) for Ecuadorian oceanic plateau basalts (OPB); Piñón basalts collected in  
1532 the Chongón-Colonche Hills (CCH) have been distinguished by a black spot. (2) Reynaud et  
1533 al. (1999) and van Melle et al. (2008) for Las Orquideas (LO) volcanic rocks, and from  
1534 Allibon et al. (2008) for the dolerites. (3) Cosma et al. (1998), Reynaud et al. (1999), Kerr et  
1535 al. (2002a), Vallejo (2007), Allibon et al. (2008), and Chiarada (2009), for island arc volcanic  
1536 rocks of the San Lorenzo Fm. and Rio Cala Arc. (4) Vallejo (2007) for the Pujili Granite.

1537

1538 Fig. 8. Variations of selected incompatible trace element contents (ppm) against SiO<sub>2</sub> (wt.%)  
1539 for the studied Pascuales basaltic lavas and felsic plutonic rocks. Data sources for other Late  
1540 Cretaceous Ecuador magmatic rocks same as Fig. 7.

1541

1542 Fig. 9. (A) Chondrite-normalized REE patterns of Pascuales tonalitic samples. (B) Chondrite-  
1543 normalized REE patterns of Pascuales trondhjemitic samples. (C) Multi-element patterns  
1544 normalized to primitive mantle (PM) of Pascuales tonalitic and trondhjemitic samples. (D)  
1545 Chondrite-normalized REE patterns of Pascuales basaltic samples. (E) Multi-element patterns  
1546 normalized to N-MORB of Pascuales basaltic samples. In panels A–C gray field is for Rio  
1547 Cala Arc volcanic rocks with  $\text{SiO}_2 \geq 56$  wt.%. In panel D gray field is for other Ecuador  
1548 oceanic plateau basalts and dolerites. Data sources for Las Orquideas, Rio Cala Arc and  
1549 oceanic plateau magmatic rocks same as Fig. 7. Normalizing values are from Sun and  
1550 McDonough (1989).

1551

1552 Fig. 10. Initial Nd, Sr and Pb isotope plots of the studied Pascuales basaltic lavas and felsic  
1553 plutonic rocks. Data for Ecuadorian OPB and Piñón (CCH) basalts and dolerites are from  
1554 Reynaud et al. (1999), Mamberti et al. (2003), Vallejo (2007) and Lapiere et al. (2000). Data  
1555 for Rio Cala Arc and San Lorenzo Fm. volcanic rocks are from Cosma et al. (1998), Reynaud  
1556 et al. (1999), Vallejo (2007), Allibon et al. (2008) and Chiarada (2009). In (A) the two Las  
1557 Orquideas (LO) samples are the MgO-rich, silica-rich volcanic rocks (Reynaud et al., 1999);  
1558 no isotope data have been published for the LO Mg-poor dacitic samples; in (B–D) data for  
1559 LO dolerites are from Allibon et al. (2008). Are also reported Tortugal picrites and alkali  
1560 basalts from Hauff et al. (2000a) and Trela et al. (2017). The fields of the Galapagos Plume,  
1561 Pacific N-MORB and pelagic sediments at 90 Ma are from Hauff et al. (2000a,b) and the field  
1562 of the Caribbean Large Igneous Province (CLIP) is after Kerr et al. (1996, 1997). The global  
1563 composition of subducting sediment (GLOSS) is Plank and Langmuir (1998), the Northern  
1564 Hemisphere Reference Line (NHRL) is from Hart (1984) and the Bulk Silicate Earth (BSE) is  
1565 from Zindler and Hart (1986).

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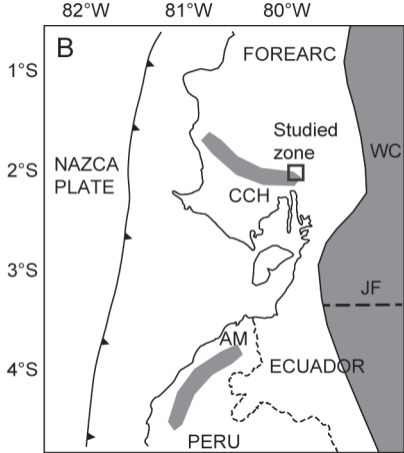
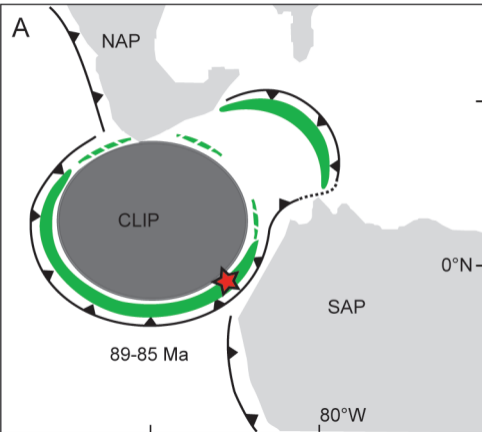
1567 Fig. 11. Variations of initial radiogenic Nd isotope vs. SiO<sub>2</sub> (wt. %) and Nb (ppm) for the  
1568 Pascuales basaltic lavas and felsic plutonic rocks and the two Las Orquideas (LO) MgO-rich,  
1569 silicica-rich volcanic rocks rocks (data from Reynaud et al., 1999). No isotopic data are  
1570 available for the LO MgO-poor dacites.

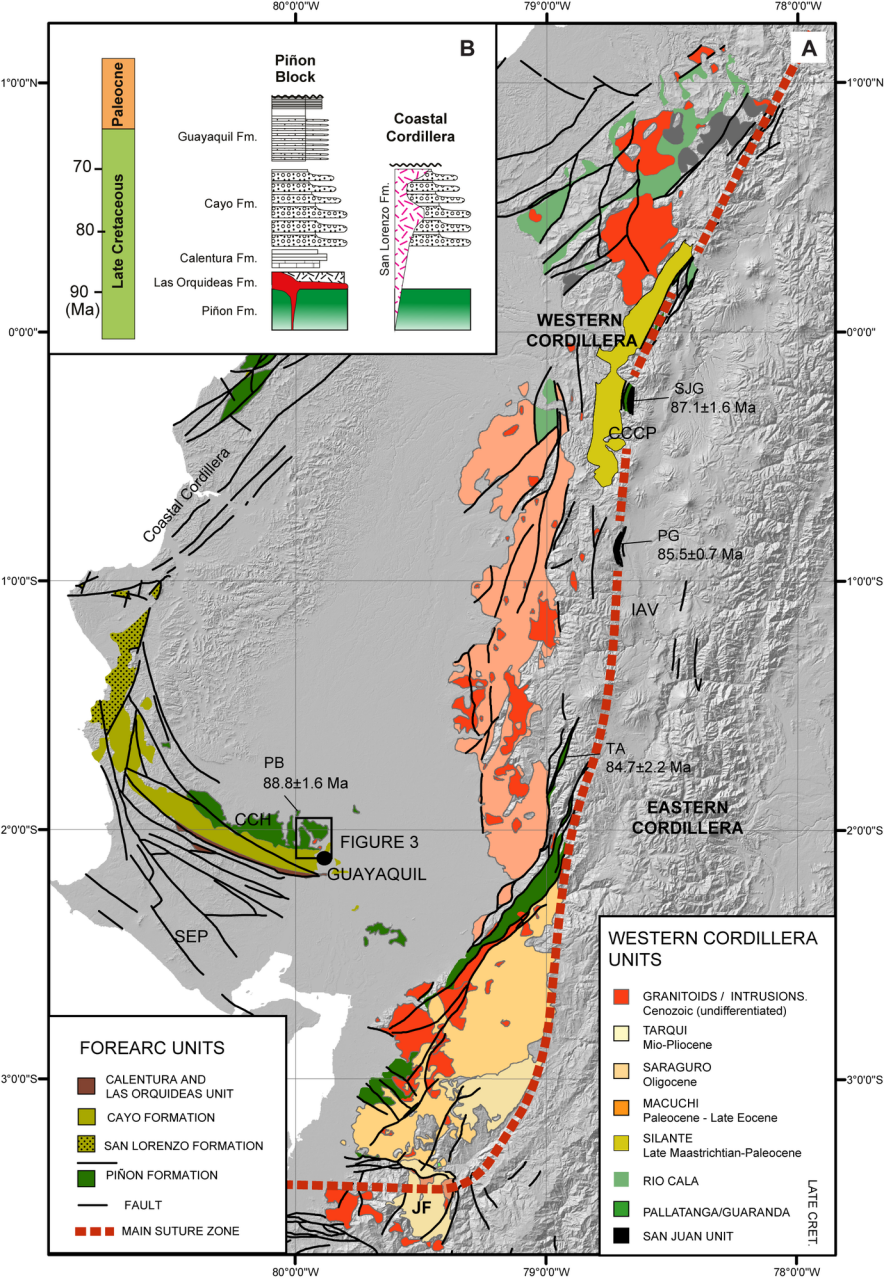
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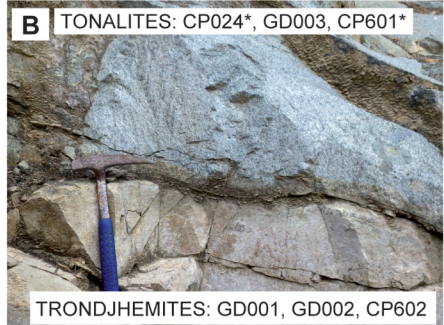
1572 Fig. 12. Comparison of Pascuales felsic (this study) and Las Orquideas (LO) dacitic  
1573 compositions with melt compositions from experiments in Harker-type diagrams. (A) K<sub>2</sub>O vs.  
1574 SiO<sub>2</sub>. (B) P<sub>2</sub>O<sub>5</sub> vs. SiO<sub>2</sub>. (C) FeO\*/MgO vs. SiO<sub>2</sub>. (D) TiO<sub>2</sub> vs. MgO. Experimental data for  
1575 fractional crystallization (FC) of arc magmas at mid to lower crustal depths: Sisson et al.  
1576 (2005), Blatter et al. (2013), Nandedkar et al. (2014), and Ulmer et al. (2018). Experimental  
1577 data for hydrous partial melting (HPM) of rocks: Koepke et al. (2004) for hydrous partial  
1578 melting of oceanic cumulate gabbros and France et al. (2010, 2014) for anatexis of  
1579 hydrothermally altered mid-oceanic ridge sheeted dikes. Initial (in.) compositions of the  
1580 gabbro protoliths (Koepke et al., 2004) are also shown. Tholeiitic (TH) and calc-alkaline (CA)  
1581 fields are from Miyashiro (1974). High FeO\*/MgO ratios of Pascuales trondhjemites are due  
1582 to very low MgO contents.

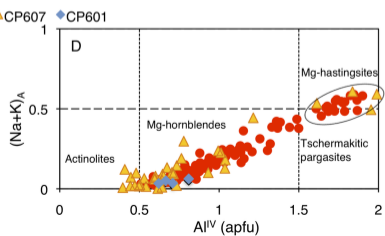
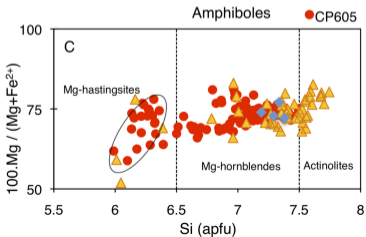
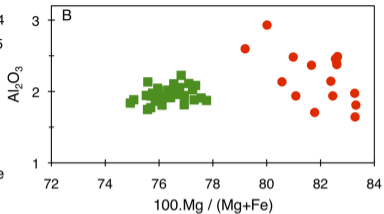
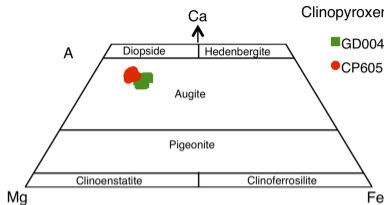
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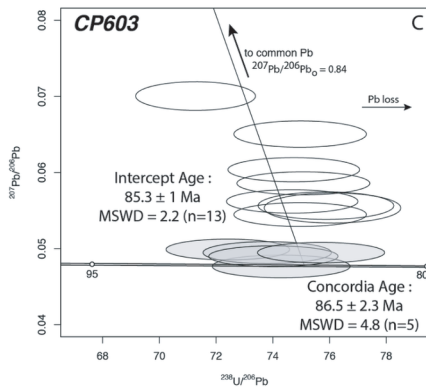
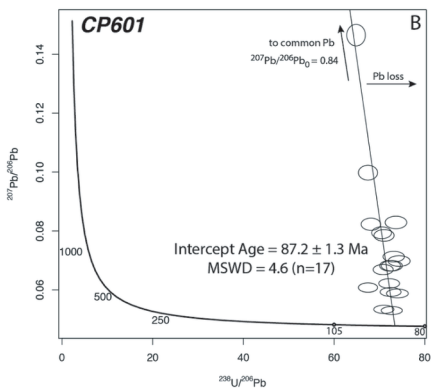
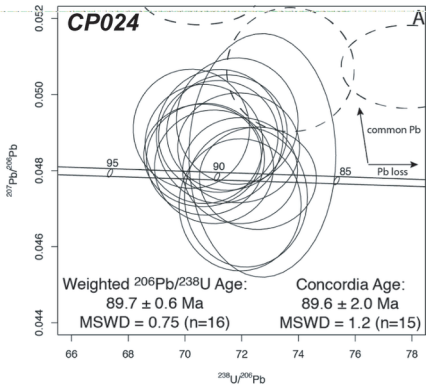
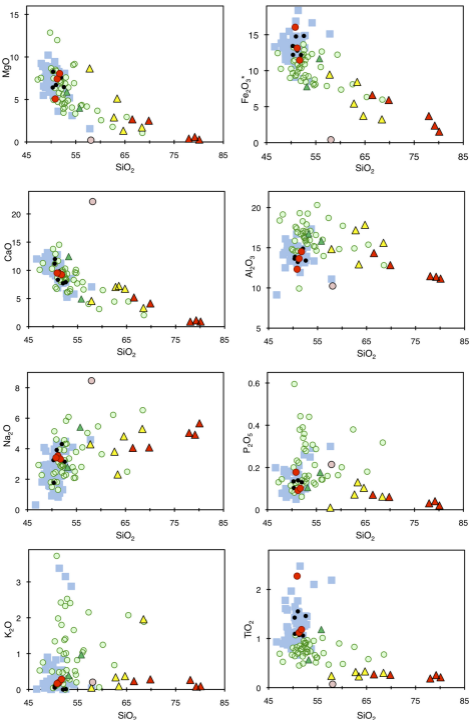


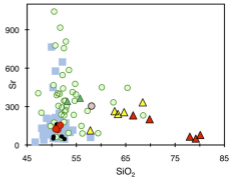
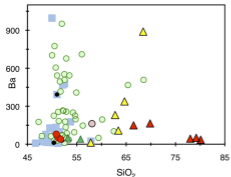
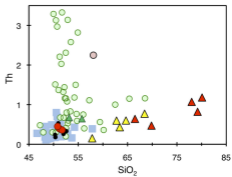
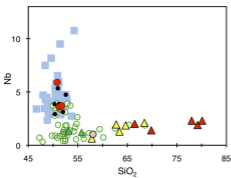
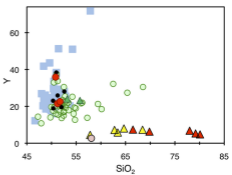
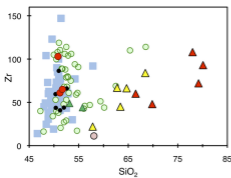
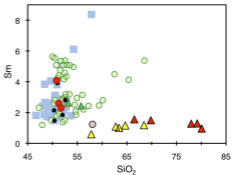
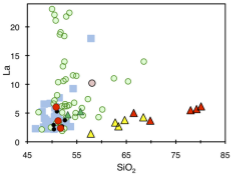
Figure 5. Seyler et al.



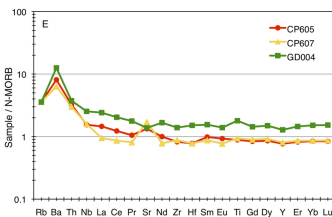
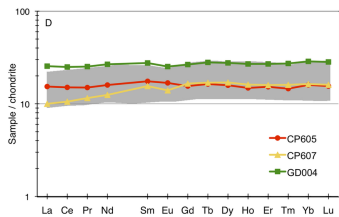
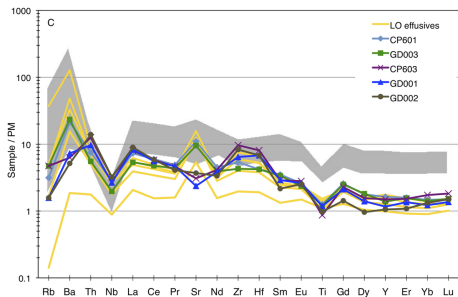
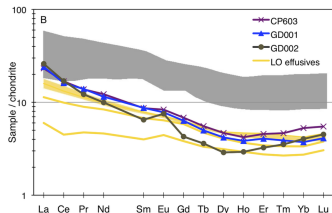
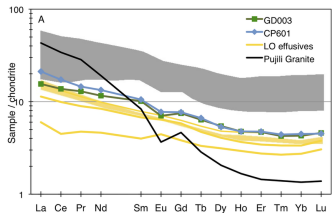


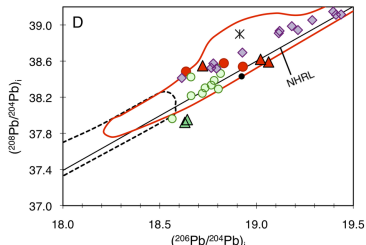
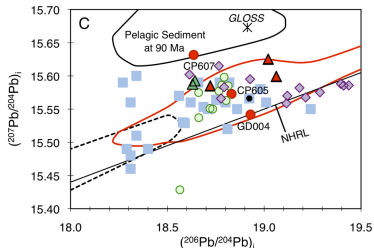
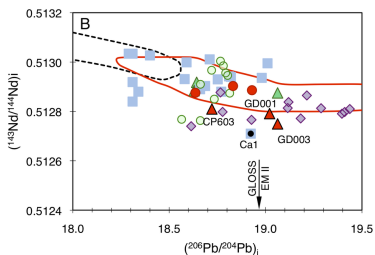
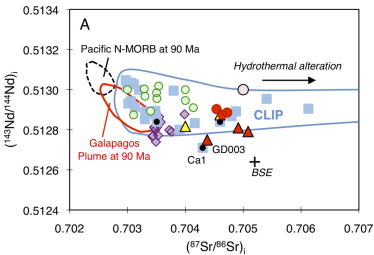
■ OPB (Ecuador)     ● Piñón (CCH)  
▲ Felsics (this study)     ● Basalts (this study)

▲ LO effusives     ○ Rio Cala-San Lorenzo  
▲ LO dolerites     ○ Pujili Granite









● Basalts (this study) ▲ Felsics (this study) ■ OPB (Ecuador)  
 ● Piñón (CCH) ▲ LO effusives ○ Pujilli Granite

○ Rio Cala-San Lorenzo ▲ LO dolerites ◆ Tortugal

