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The birth of the Gondwanide arc: Insights into Carboniferous magmatism of the North Patagonian Andes (Argentina)

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32 **Keywords:** Primitive arc melts, Gondwanide orogeny, Late Paleozoic, sheeted zones, Western  
33 Gondwana.

34

## 35 **1. Introduction**

36 Subduction-related magmatism occurs in the upper continental plate of convergent margins,  
37 driven by dehydration reactions in the downgoing slab (Gill, 1981) and the ascent of melange  
38 diapirs (Marschall and Schumacher, 2012). The magmatism formed above subduction zones is  
39 thus characterized by significant amounts of volatiles and has an extensive range of silica  
40 contents, calc-alkaline compositions, and distinct trace element patterns. The great majority of  
41 Cordilleran batholiths are intermediate (tonalite to granodiorite) in composition, whereas  
42 gabbroic intrusions are subordinate and more common during primitive stages of arc  
43 construction (e.g., Schmidt and Jagoutz, 2017). Therefore, arc magmatism requires additional  
44 controls during its evolution, such as magmatic differentiation, fractional crystallization, host  
45 rock assimilation, partial melting, or a combination of them. All these processes can generate  
46 silica enrichment, resulting in modified geochemical trends from a primary mantle source  
47 (Ducea et al., 2015 and references therein).

48 The Gondwanide orogeny comprises one of the most exceptional tectono-magmatic records of  
49 the Earth history (e.g., Cawood et al., 2011). In southern South America, the beginning of this  
50 orogeny is characterized by an active continental arc built along the proto-Andean margin  
51 (Llambías et al., 1993; Pankhurst et al., 2006; Dahlquist et al., 2018). However, the Gondwanide  
52 magmatism shows a protracted evolution from the late Mississippian to the Triassic south of 39°  
53 (Llambías et al., 1984; Sato et al., 2015; Alasino et al., 2022). This evolution is particularly well-  
54 documented in the Patagonian region, where Carboniferous to late Permian intrusions monitor  
55 spatio-temporal variation of arc dynamics (e.g., Pankhurst et al., 2006; Varela et al., 2005, 2015;  
56 Oriolo et al., 2022).

57 This work focuses on Carboniferous magmatism exposed in the North Patagonian Andes  
58 between the Guillermo lake region and the Cordón del Serrucho. Geological, geochemical,  
59 barometric, structural, and microstructural data are integrated to characterize their nature and  
60 petrogenesis. In addition, the tectonomagmatic setting in the context of the Gondwanide arc  
61 dynamics along the southwestern Gondwana margin is assessed.

62

63

## 64 2. Geological setting

65 In southern South America, the Gondwanide magmatism is well-documented and has been  
66 defined as different igneous cycles between the Late Paleozoic and Late Triassic (Llambías et al.,  
67 1984; Sato et al., 2015; Gregori et al., 2020; Alasino et al., 2022). The beginning of this cycle is  
68 recorded along discontinuous pre-Andean outcrops (e.g., Llambías et al., 1993; Alasino et al.,  
69 2012; del Rey et al., 2016; Dahlquist et al., 2018, 2021). Particularly, the Paleozoic magmatism  
70 in northwestern Patagonia, is exposed between the North Patagonian Cordillera and the North  
71 Patagonian Massif (Fig. 1 and Table 1; Varela et al., 2005). In the former, middle to late  
72 Carboniferous magmatism crops out in the Cordón del Serrucho and further south at Cañadón  
73 de la Mosca, and is considered part of the Colohuincul Complex (Giacosa et al., 2001; Varela et  
74 al., 2005, 2015; Pankhurst et al., 2006). During the Permian and Triassic, widespread igneous  
75 activity continued, evolving from calc-alkaline orogenic associations to alkaline postorogenic  
76 sequences (e.g., Pankhurst et al., 2006). Permian magmatism in the western North Patagonian  
77 Massif corresponds to the Mamil Choique Formation and is exposed near Piedra del Águila and  
78 the Sierra Mamil Choique (Volkheimer, 1964; Ravazzoli and Sesana, 1977; Proserpio, 1978;  
79 Cerredo and López de Luchi, 1998; Varela et al., 2005, 2015; Pankhurst et al., 2006).

80 In the southwestern Gondwana region, the Gondwanide magmatism is part of the igneous-  
81 metamorphic northern Patagonian basement, including both magmatic foliated and non-  
82 foliated facies. It occurs together with metasedimentary sequences, as in the case of the  
83 Colohuincul Complex (Dalla Salda et al., 1991; García-Sansegundo et al., 2009). In general, the  
84 late Carboniferous-Permian magmatism exhibits dominantly calc-alkaline trends, meta- to  
85 peraluminous, and I- to S-type compositions (Varela et al., 2005, 2015; Pankhurst et al., 2006).  
86 Notably, the North Patagonian Andes basement between the Mascardi lake in the north and the  
87 Cordón del Serrucho to the south presents significant exposures of Carboniferous igneous-  
88 metamorphic basement rocks (Figs. 1 and 3). However, these rocks have alternatively been  
89 attributed to either Late Carboniferous intrusions or amphibolites/metasedimentary sequences  
90 of the Colohuincul Complex (Dalla Salda et al., 1991; Giacosa and Heredia, 2001; Varela et al.,  
91 2005, 2015; Pankhurst et al., 2006; García-Sansegundo et al., 2009).

92 In the southeastern North Patagonian Massif (Fig. 1), Late Carboniferous magmatism  
93 corresponds to the El Platero tonalite, with an age of  $329 \pm 4$  Ma (Fig. 1; Pankhurst et al., 2006).  
94 Likewise, Late Carboniferous magmatism was also identified in Paso del Sapo and Sierra de los  
95 Pichiñanes, with ages of  $314 \pm 2$  and  $318 \pm 2$  Ma, respectively (Pankhurst et al., 2006; Renda et  
96 al., 2021). Finally, Permian magmatism is also present in the region, with Cisuralian intrusions



97 such as the El Tunel tonalite in Río Chico ( $295 \pm 2$  Ma), the Laguna del Toro granodiorite near  
98 Gastre ( $294 \pm 3$  Ma), and the Mamil Choique Formation ( $281 \pm 2$  Ma) in the homonymous range  
99 (Varela et al., 2005; Pankhurst et al., 2006).

100 Further north, Late Paleozoic magmatism is present in the Precordillera Neuquina, as indicated  
101 by the Chachil Plutonic Complex, which intrudes the Piedra Santa metasedimentary complex  
102 and yields U-Pb zircon ages of  $303 \pm 2$  Ma,  $300 \pm 2$  Ma,  $305 \pm 2$  Ma, and  $358 \pm 2$  Ma (Franzese,  
103 1995; Romero et al., 2019; Oriolo et al., 2022). Based on petrological and age similarities, the  
104 Chachil Plutonic Complex can be correlated with coeval plutons of the Coastal Batholith of Chile  
105 between  $37$  and  $41^\circ\text{S}$  (Hervé et al., 1984; Varela et al., 1994; Franzese, 1995; Romero et al.,  
106 2019).

107 At the southern North Patagonian Cordillera, in the Cordón del Serrucho area, Carboniferous  
108 biotite- and hornblende-bearing foliated granodiorites present a U-Pb SHRIMP zircon age of  $330$   
109  $\pm 4$  Ma (Pankhurst et al., 2006). In addition, comparable intrusions yielded U-Pb ages of  $324 \pm 2$   
110 Ma (Oriolo et al., 2022) and  $323 \pm 3$  Ma (Varela et al., 2005, 2015; Pankhurst et al., 2006) at  
111 Morro de Sheffield and Cañadón de la Mosca areas, respectively.

112 The basement rocks of the Guillermo lake study area (Fig. 1) were first described as diorite  
113 igneous bodies (Feruglio, 1941) and then as amphibolites assigned to the Colohuincul Complex  
114 with K-Ar hornblende ages of  $344 \pm 30$  and  $329 \pm 24$  Ma (Dalla Salda et al., 1991; García-  
115 Sansegundo et al., 2009). Recent U-Pb LA-ICP-MS zircon analyses on the diorites yielded an age  
116 of  $325 \pm 4$  Ma (Oriolo et al., 2022). Consequently, these basement rocks have an ambiguous  
117 interpretation, similar to those exposed further south in the Cañadón de la Mosca, which have  
118 alternatively been described as amphibolites or diorites-tonalites (Varela et al., 2005; Pankhurst  
119 et al., 2006).

### 120 **3. Methodology**

121 Geological and structural mapping was carried out by combining Landsat 8 image processing  
122 with new field data (Fig. 2) and published maps (González Bonorino, 1944; Feruglio, 1947; Dalla  
123 Salda et al., 1991; Giacosa and Heredia, 2001; García-Sansegundo et al., 2009). Fieldwork  
124 included structural data collection and sampling for petrographic and geochemical analysis.  
125 Structural data were processed with Stereonet (Allmendinger et al., 2012; Cardozo et al., 2013).

126 For geochemical characterization, whole-rock analyses were carried out at AcmeLabs, Canada  
127 (<http://acmelab.com/>) for major, trace, and rare earth elements using lithoborate fusion and  
128 ICP-MS methods. Results of the new geochemical data are exhibited in Supplementary

129 Material\_1. Data analysis, including analyses published by Dalla Salda et al. (1991), Pankhurst et  
130 al. (2006), García-Sansegundo et al. (2009), and Varela et al. (2015), was carried out with GCDKit  
131 6.0 (Janousek et al., 2006, 2016). Although García-Sansegundo et al. (2009) also reported  
132 analysis of granitic bodies, these were not included due to mapping criteria, as they may likely  
133 be of Jurassic age (e.g., Castro et al., 2011).

134 Additionally, a JEOL JXA-8530F electron probe microanalyzer at the Institute of Earth Science of  
135 the University of Lausanne (Switzerland) was used to acquire quantitative analyses of  
136 amphiboles. Spot analyses were performed using an accelerating voltage of 15 keV. To avoid  
137 electron-beam induced decomposition of amphibole that normally contains volatile elements,  
138 a current of 15 nA was applied for. A beam size ranging between 2 and 5  $\mu\text{m}$  was used depending  
139 on the size of the mineral. Al-in-Hornblende barometric estimations were based on the  
140 calibrations of Schmidt et al. (1992) and Mutch et al. (2016). Analytical results are shown in  
141 Supplementary Material\_2.

## 142 **4. Results**

### 143 **4.1 Lithological characterization**

144 Carboniferous igneous rocks of the study area are grouped in a batholith of at least ca. 300 km<sup>2</sup>,  
145 elongated in a NNW-SSE direction (Fig. 2). At the Guillermo lake area, it consists of magmatic  
146 foliated diorites and subordinate foliated quartz-diorites, tonalites, and gabbros (Fig. 3A), being  
147 comparable those exposed in the Cañadón de la Mosca (Fig. 3B). Further south, more felsic rocks  
148 are generally dominant in the Cordón del Serrucho, corresponding mainly to diorites and quartz-  
149 diorites, whereas intercalated diorites and gabbros crop out at the southernmost exposures at  
150 the Morro de Sheffield. Microgranular mafic enclaves are frequent in all these rocks (Fig. 3C).

151 All rocks typically include magmatic structures. Magmatic foliation and lineation are well-  
152 defined by the shape-preferred orientation of euhedral amphibole and plagioclase. Parallel to  
153 the foliation, compositional layering with gabbro to diorite/tonalite alternating bands is  
154 common (Fig. 3D-E). In some cases, this layering defines areas of sheeted plutons and schlieren  
155 (Fig. 3F). When present, elongated microgranular enclaves are often parallel to the foliation.  
156 However, local high-temperature solid-state fabrics resulting in dioritic orthogneisses were  
157 recorded as well, mainly at the northeastern margin of the pluton close to the contact with the  
158 country rocks and also locally in different sectors of the pluton.

159 The country rocks of the batholith are exposed at the northeastern part of Guillermo lake. It  
160 consists of paragneisses, schists, and minor amphibolites with a dominantly WNW-ESE-striking

161 foliation, which dips moderately to the SSW. The intrusive contact is poorly exposed, as pluton  
162 margins are mainly overprinted by younger Jurassic intrusions or covered by vegetation or  
163 Cenozoic sequences.

#### 164 **4.2 Structure**

165 The magmatic foliation of rocks is nearly ubiquitous and lies parallel to the compositional  
166 layering and trails of elongated enclaves, which are present in some cases (Fig. 3). These fabrics  
167 are dominantly oriented in NNW-SSE to WNW-ESE direction (Fig. 2). At the Guillermo lake, the  
168 foliation strikes NNW-SSE to NW-SE and shows mainly moderate to gentle dips towards the  
169 SSW/SW. The orientation of associated lineations is more scattered, plunging either gently to  
170 the SE or moderately to the WSW-NW. At the Cañadón de la Mosca, the magmatic foliation  
171 strikes NNW-SSE and moderately dips to the ENE. In the case of Cordón del Serrucho and Morro  
172 de Sheffield, a NW-SE to WNW-ESE-striking foliation is documented, with moderate to steep  
173 dips to the SSW/SW and NNE/NE, though the former seems to be dominant. Moderate to gentle  
174 plunge toward the S/SSE characterizes lineations. Besides structures that describe the internal  
175 fabric of the body, igneous rocks are cross-cut by ductile to brittle-ductile shear zones and faults,  
176 at outcrop scale. Shear zones comprise mylonitic bands exposed at the western margin of the  
177 Guillermo lake, overprinting dioritic rocks, which are cross-cut by late fault zones.

#### 178 **4.3 Petrography and microstructures**

179 The rocks of the study area correspond to amphibole  $\pm$  biotite quartz-diorites, diorites, and  
180 subordinate gabbros, according to the QAP diagram of plutonic rocks (Le Maitre, 2002; Fig. 4A-  
181 B). Apatite, titanite, rutile, zircon, magnetite and other opaque minerals are accessory minerals.  
182 Alteration to epidote and chlorite is also observed in some cases.

183 Amphibole and plagioclase crystals are aligned, defining a shape-preferred orientation (Fig. 4A).  
184 As observed in the field, the magmatic layering is also evidenced at microscopic scale,  
185 documented by alternating mafic and felsic bands of variable grain sizes (Fig. 4B).

186 Likewise, the rocks record other magmatic features, such as zoned euhedral plagioclase crystals  
187 (e.g., Paterson et al., 1989). Nevertheless, granoblastic quartz and plagioclase evidence local  
188 high-temperature solid-state static recrystallization (Fig. 4C-D). Or else, secondary and bent  
189 twins also document medium-temperature solid-state deformation (Fig. 4E). Locally, more  
190 deformed rocks also record the local development of plagioclase porphyroclasts, core-and-  
191 mantle microstructures in feldspars, and subgrains suggesting medium- to high-temperature  
192 dynamic recrystallization (Fig. 4F).

## 193 4.4 Whole-rock geochemistry

### 194 4.4.1 Major elements

195 Whole-rock geochemistry were carried out in samples BA33-17, BA13-2-20, BA13-3-20, BA19-  
196 20 and SE8-19A). The igneous rocks of the Guillermo-Serrucho Plutonic Complex have a silica  
197 content of ca. 45 – 60 wt. %, whereas Fe<sub>2</sub>O<sub>3</sub> (total Fe), MgO and CaO lie between 5-12, 2-8 and  
198 5-9 wt. %, respectively. The alkali content is low to intermediate (ca. 2.5-5% for Na<sub>2</sub>O and 0.3-  
199 1.7% for K<sub>2</sub>O) (Supplementary Material\_1). In the TAS diagram (Middlemost, 1994; Fig 5A),  
200 samples plot mainly in gabbro-diorite to diorite fields and minor gabbro and granodiorite. Most  
201 samples correspond to the tholeiitic to calc-alkaline series according to the SiO<sub>2</sub> vs. K<sub>2</sub>O diagram  
202 of Pecерillo and Taylor (1976) (Fig. 5B). The AFM diagram (Irvine and Baragar, 1971; Fig. 5C)  
203 depicts a similar trend, where calc-alkaline samples predominate over tholeiitic.

204 In the discrimination diagrams of Frost et al. (2001), samples are characterized by magnesian,  
205 metaluminous, and calcic to calc-alkalic composition (Figs. 5D-F). Thus, the batholith exhibits  
206 geochemical features comparable to those of Cordilleran granitoids.

### 207 4.4.2 Trace elements

208 The trace element diagram normalized to N-MORB (Sun and McDonough, 1989) shows an  
209 enrichment in LILE concerning HSFE (Fig. 6A). In general, all samples present a negative Nb  
210 anomaly and positive K and Pb anomalies. Nevertheless, Guillermo lake samples seem to be less  
211 enriched in LILE than samples of other locations. The Cordón del Serrucho rocks exhibit a similar  
212 trend but seem the most enriched in trace elements (Fig. 6A)

213 Chondrite-normalized rare earth element diagram (Boynnton, 1984) contents show a slight  
214 enrichment in LREE regarding HREE, which is clear in all samples (Fig. 6B). La<sub>N</sub>/Yb<sub>N</sub> ratio are low  
215 and vary between 1.55 (BA13-2-20, Guillermo Lake) and 6.56 (SER-044, Cordón del Serrucho,  
216 Pankhurst et al., 2006). Samples of the Guillermo lake are less enriched in REE than the remaining  
217 (Figure 6B). Moreover, there is a minor positive Eu anomaly in samples of the Guillermo lake,  
218 with Eu/Eu\* values varying between 1.12 and 1.40, whereas most of the samples from Cañadón  
219 de la Mosca and Cordón del Serrucho present a negligible to slightly positive anomaly in Eu, with  
220 Eu/Eu\*, with values of 1.12.

221 The generally low Dy/Yb and Nb/Ta contents suggest the dominance of amphibole fractionation  
222 in the source (Fig. 7A-B; Fischer and Marty, 2005; Macpherson et al., 2006; Davidson et al., 2007;  
223 Ming Tang et al., 2019). Therefore, garnet in the source seems to be nearly absent, as further  
224 supported by relatively low La<sub>N</sub>/Yb<sub>N</sub> values. As documented by minor negative Ti anomalies, the

225 fractionation of Ti-bearing phases may be feasible, though this process may be subordinate due  
226 to the low Nb/Ta values (Fig. 7C; John et al., 2011). On the other hand, the dominance of  
227 negligible to slightly positive Eu anomalies rules out plagioclase fractionation in the source. The  
228 slightly positive Eu/Eu\* values may indicate very subordinate plagioclase accumulation (e.g.,  
229 Dessimoz et al., 2012). The latter process, coupled with dominant amphibole fractionation, may  
230 thus account for the positive correlation between Eu/Eu\* and Sr/Y (Fig. 7; Dessimoz et al., 2012;  
231 Oriolo et al., 2022).

232 As seen in the Nb/Yb vs. Th/Yb diagram of Pearce (2008) (Fig. 8), most samples deviate from the  
233 MORB-OIB array towards the volcanic arc array, with only one sample of the Guillelmo lake in  
234 the MORB-OIB field. The general trend indicates a MORB mantle source, possibly with a  
235 composition between N-MORB and E-MORB. This trend shows crustal components and may  
236 suggest possible metasomatism in the mantle source, if a slightly enriched source is assumed. In  
237 addition, the magmatic arc affinity is also supported by trace element patterns (Fig. 6) and  
238 discrimination diagrams of Pearce et al. (1984), where all the samples are located within the  
239 VAG field (Fig. 9).

#### 240 **4.5 Mineral chemistry and amphibole barometry**

241 Amphibole mineral chemistry and barometry were carried out in samples BA 33-17 and SE8-19A  
242 of foliated diorites. Analytical results were analysed using the templated of Ridolfi (2021),  
243 whereas calibrations of Schmidt et al. (1992) and Mutch et al. (2016) were considered for  
244 barometric estimations (Fig. 10). There are no systematic variations within or between samples,  
245 with compositions corresponding to calcic amphiboles, namely tschermakite and  
246 magnesiohornblende, according to Leake et al. (1997) (Fig. 11).

247 Rocks of the Guillelmo-Serrucho Plutonic Complex have magnetite in its composition and, in  
248 fact, are ferromagnetic rocks. That is an important point for calibrations because they are based  
249 on oxygen fugacity ( $fO_2$ ), with  $fO_2$  above QFM (quartz-fayalite-magnetite) and below HM  
250 (hematite-magnetite) (Schmidt et al., 1992). Thus, the presence of magnetite ensures that it is  
251 working in a correct range of  $fO_2$  for a correct use of the barometer.

252 According to the calibration of Schmidt et al. (1992), the obtained pressure for sample BA33-17  
253 corresponds to a weighted average of  $6.98 \pm 0.31$  kbar and, for sample SE8-19A, to a weighted  
254 average of  $6.22 \pm 0.18$  kbar. On the other hand, pressures based on Mutch et al. (2016) yielded  
255 weighted average values of  $5.40 \pm 0.39$  kbar for sample BA33-17 and  $4.89 \pm 0.18$  kbar for sample  
256 SE8-19. Both calibrations were also applied to experimental results of Mutch et al. (2016).  
257 Though both calibrations can be applied for plutonic rocks, there is less difference between

258 experimental and calculated results using the Mutch et al. (2016) calibration than using the  
259 Schmidt et al. (1992) calibration. Therefore, pressure determinations based on Mutch et al.  
260 (2016) may be more representative for this study.

## 261 **5. Discussion**

### 262 **5.1 The Guillermo-Serrucho Plutonic Complex: a record of synorogenic primitive arc** 263 **magmatism**

264 The basement rocks in the study area have been classically considered amphibolites, as part of  
265 the Colohuincul or Bariloche Complex (Dalla Salda et al., 1991; García-Sansegundo et al., 2009;  
266 Oriolo et al., 2019). However, new geological, structural, microstructural, and geochronological  
267 evidence allows to separate this igneous body from the adjacent metasedimentary rocks.

268 In this regard, the “Guillermo-Serrucho Plutonic Complex” is proposed to gather the middle to  
269 late Carboniferous intrusive bodies into a batholith cropping out between the Guillermo lake  
270 region and the Cordón del Serrucho. Besides petrological and structural similarities, this  
271 correlation is further supported by ages of ca. 330-323 Ma revealed by U-Pb SHRIMP and LA-  
272 ICP-MS zircon data (Fig. 2; Pankhurst et al., 2006; Oriolo et al., 2022).

273 The batholith mainly comprises foliated diorites, quartz-diorites, and subordinate gabbros and  
274 tonalites. It presents well-defined magmatic foliation and lineation, compositional layering, and  
275 trails of mafic microgranular enclaves to a lesser extent and locally exhibits high-temperature  
276 solid- state microstructures related to cooling (Paterson et al., 1989), particularly at the  
277 northeastern margin of the pluton.

278 The widespread occurrence of NNW-SSE- to WNW-ESE-striking magmatic fabrics, which are  
279 comparable to metamorphic fabrics in the metasedimentary country rock (Fig. 3; Dalla Salda et  
280 al., 1991; García-Sansegundo et al., 2009; Oriolo et al., 2019), indicates a highly coupled system  
281 (Paterson et al., 1998; Paterson et al., 2019). Batholith emplacement thus occurred in an  
282 orogenic setting linked with transpressional deformation (García-Sansegundo et al., 2009; Oriolo  
283 et al., 2019). Field relationships and geochronological constrains show that the oldest intrusions  
284 (ca. 330 Ma) are rather felsic (e.g., Cordón del Serrucho quartz-diorites), though they show  
285 evidence of mingling, as documented by microgranular mafic enclaves. In addition, the late  
286 emplacement of more mafic intrusions at ca. 325-323 Ma suggest mafic magma replenishment.  
287 These observations thus point to incremental growth of batholith construction in less than ca.  
288 10 My, possibly controlled by a regional ductile flow and transpressional deformation (e.g.,  
289 Ingram and Hutton, 1994; Paterson and Miller, 1998; Miller and Paterson, 2001; Zak et al., 2009;

290 Pinotti et al., 2016). Further evidence is provided by thermobarometric data of the  
291 metasedimentary country rock, which shows a prograde path from ca. 6-8 to 10-12 kbar (Oriolo  
292 et al., 2019). Monazite EPMA Th-U-Pb data yielded ages of ca. 300 Ma for the timing of peak  
293 metamorphic conditions (or the subsequently decompression path), thus indicating a late  
294 Carboniferous age for the prograde path (Oriolo et al., 2019). Therefore, barometric results  
295 obtained for the Guillelmo-Serrucho Plutonic Complex, which are comparable to the early  
296 pressure estimations for the country rock P-T path, may roughly indicate an emplacement during  
297 the onset of transpressional progressive deformation of the Bariloche Complex.

298 On the other hand, geochemical data indicate a primitive arc composition and have features  
299 comparable to Cordilleran granitoids (Fig. 5D-F, Frost et al., 2001; Schmidt and Jagoutz, 2017,  
300 and references therein), showing an incipient continental crust signature. This is further  
301 supported by isotopic compositions, with values of  $Sr/Sr_0$  of 0.704374 and 0.704625,  $\epsilon Nd$   
302 between -0,6 and 1.2 and  $\epsilon Hf$  between 2.5 and 4.5 (Varela et al., 2005; Pankhurst et al., 2006;  
303 Fanning et al., 2011). The magmatic arc affinity is also supported by discrimination diagrams of  
304 Pearce et al. (1984) (Fig. 9). The slight deviation from the depleted mantle isotopic composition  
305 may indicate a slightly metasomatized source due to subduction, as evidenced by trace element  
306 data (Fig. 7). Alternatively, the crustal contribution might have resulted from minor assimilation  
307 of country rock during magma ascent and emplacement. In addition, barometric data coupled  
308 with the dominance of amphibole fractionation in the source (Section 4.5) points to  
309 middle/lower crustal depths resulting from the onset of the Gondwanide orogeny (Oriolo et al.,  
310 2022; see section 5.2).

311 On the other hand, the dominance of amphibole fractionation is clear according to low Dy/Yb  
312 and Nb/Ta contents (Fig. 7A-B; Fischer and Marty, 2005; Macpherson et al., 2006; Davidson et  
313 al., 2007; Ming Tang et al., 2019), while plagioclase seems to be very subordinate according to  
314  $Eu/Eu^*$  and Sr/Y (Fig. 7; e.g., Dessimoz et al. 2012). In addition, garnet in the source seems to be  
315 nearly absent, as further supported by relatively low  $La_N/Yb_N$  values. Minor negative Ti  
316 anomalies documented the feasible fractionation of Ti-bearing phases.

317

## 318 **5.2 Petrotectonic context and regional implications**

319 Following the early Carboniferous magmatic lull after widespread Devonian arc magmatism  
320 (e.g., Varela et al., 2005, 2015; Pankhurst et al., 2006; Hervé et al., 2016; Rapela et al., 2021;  
321 Oriolo et al., 2022), magmatism resumes at ca. 330 Ma in northern Patagonia, as documented  
322 by the Guillelmo-Serrucho Plutonic Complex. This early pulse at ca. 330-323 Ma represents the



323 only primitive arc signature so far reported for the Gondwanide magmatism, as subsequent late  
324 Carboniferous to Permian intrusions is generally more evolved (e.g., Varela et al., 2005, 2015;  
325 Pankhurst et al., 2006; Oriolo et al., 2022). NW-SE magmatic structures in late Carboniferous-  
326 early Permian syntectonic granitoids, such as those recorded herein, match coeval NW-SE  
327 deformational fabrics in associated metamorphic rocks (Cerrodo and López de Luchi, 1998; von  
328 Gosen, 2003, 2009; Giacosa et al., 2004; Oriolo et al., 2019; Renda et al., 2019, 2021). On a  
329 regional scale, igneous and metamorphic rocks delineate a NW-SE-striking regional belt,  
330 recording transpression and medium- to high-grade metamorphism in a continental magmatic  
331 arc (Renda et al., 2019, 2021; Oriolo et al., 2019; Marcos et al., 2020).

332 That magmatic arc has a NW-SE orientation in the Andean and extra-Andean Patagonian region  
333 of Argentina (Renda et al., 2019), whereas further northwest, it has a N-S orientation, mainly  
334 revealed by the Coastal Batholith of Chile (Fig. 12). The latter comprises calc-alkaline granitoids  
335 that were emplaced between ca. 320-300 Ma at ca. 35-40°S (Deckart et al., 2014). Though  
336 Gondwanide arc magmatism is also exposed further north, Alasino et al. (2022) showed two  
337 main age peaks at ca. 340 and 305 Ma associated with crustal thinning, which are succeeded by  
338 crustal thickening at ca. 280 Ma during the San Rafael Orogeny. This evolution contrasts  
339 significantly with that observed for northern Patagonia, where a magmatic gap is observed at  
340 ca. 340 Ma and synorogenic magmatism linked with crustal thickening is documented at ca. 330-  
341 300 Ma (e.g., Oriolo et al., 2019; Renda et al., 2019, 2021; Marcos et al., 2020), thus indicating a  
342 significant along-strike segmentation of the proto-Pacific marginal arc dynamics during the  
343 Carboniferous. Several coeval plutonic bodies are exposed between the northern North  
344 Patagonian Cordillera and the north-western North Patagonian Massif (Pankhurst et al., 2006;  
345 Varela et al., 2005, 2015; Hervé et al., 2013, 2018; Renda et al., 2019; Romero et al., 2019;  
346 Gregori et al., 2021; Oriolo et al., 2022). In the extra-Andean region, Renda et al. (2019)  
347 recognized multiples blocks of igneous-metamorphic rocks aligned in the NW-SE direction,  
348 where late Carboniferous plutons exhibit magmatic fabrics comparable to those recorded  
349 herein. Further intrusions in this area, such as the La Potranca leucogranite ( $289 \pm 2$  Ma;  
350 Pankhurst et al., 2006), present differences in the internal structure and are thus interpreted as  
351 post-tectonic granites (Renda et al., 2019).

352 In sum, magmatic fabrics indicate regional deformation during the emplacement (Renda et al.,  
353 2019). These syntectonic plutonic bodies were associated with the late Paleozoic Gondwanide  
354 active margin, documenting highly coupled magmatic systems at ca. 330-314 Ma (Fig. 12).

355



**356 6. Conclusions**

357 Paleozoic basement rocks in the study area (North Patagonian Andes, Argentina) are mainly  
358 diorites and quartz-diorites with subordinate gabbros. These rocks are assigned to the  
359 Guillermo-Serrucho Plutonic Complex and contrast significantly with metasedimentary  
360 sequences of the Colohuincul or Bariloche Complex, which represent their wall rock.

361 The Guillermo-Serrucho Plutonic Complex is characterized by widespread occurrence of  
362 NNWSSE- to WNW-ESE-striking magmatic fabrics, which indicate emplacement in a tectonically  
363 active setting. Similarities between these magmatic fabrics and those of the country rock  
364 indicate a highly coupled system, emplaced in an orogenic transpressional setting linked with  
365 the Gondwanide Orogeny. Field evidence, together with geochemical and geochronological  
366 data, suggest mafic magma replenishment during construction of a relatively large batholith (at  
367 least ca. 300 km<sup>2</sup>) in a timespan of ca. <10 My. This batholith yields a primitive arc composition  
368 and documents the onset of Gondwanide subduction along the proto-Pacific margin of  
369 Gondwana.

370 The studied plutons are related to other bodies in the North Patagonian Andes and North  
371 Patagonian Massif, as well as plutonic bodies in Cordillera de la Costa of Chile, which are part of  
372 the Coastal Batholith. All these rocks have similar lithological, structural and geochemical  
373 characteristics, indicating widespread synorogenic arc pluton emplacement at ca. 330-314 Ma  
374 along the late Paleozoic Gondwanide active margin.

375

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608 Table 1. Samples, type rock, localities and geological area and zircon U-Pb geochronological data  
609 included in the map of Figure 1. References: 1. Pankhurst et al. (2006); 2. Romero et al. (2019);  
610 3. Oriolo et al. (2022); 4. Renda et al. (2021). (NPM: North Patagonian Massif; NPC: North  
611 Patagonian Cordillera; PCN: Precordillera Neuquina).

612 Figure 1. Regional sketch map modified from Pankhurst et al. (2006) and Oriolo et al. (2019).  
613 Zircon U-Pb SHRIMP and LA-ICP-MS data of Carboniferous to Permian intrusions are also  
614 included (see Table 1 for further details).

615 Figure 2. Geological map with structural data of the studied area (modified after Feruglio, 1947;  
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617 García Sansegundo et al., 2009; Santonja et al., 2021). Ages taken from Pankhurst et al. (2006)  
618 and Varela et al. (2015). Lower hemisphere equal area projections of poles of magmatic foliation  
619 (black dots) and lineation (red dots) are shown. Data of metamorphic foliation of the country  
620 rock (Bariloche Complex) is shown in the red diagram.

621 Figure 3. Magmatic foliated rocks present in the study area. Amphibole and plagioclase crystals  
622 define the foliation at the Guillermo lake margins (A) and the Cañadón de la Mosca area (B). C.  
623 Elongated microgranular mafic enclaves subparallel to foliation. D-E. Compositional layering at  
624 Morro de Sheffield and Guillermo lake zones, respectively. F. Magmatically folded and faulted  
625 mafic layering (schlieren) at Cordón del Serrucho zone.

626 Figure 4. Photomicrographs (crossed polars). A. Shape-preferred orientation of hornblende (Hbl)  
627 and plagioclase (Pl) crystals defining the magmatic foliation. B. Magmatic compositional  
628 layering. C-D. Polygonal granoblastic quartz (C)-plagioclase (D) aggregates, indicated by arrows.  
629 E. Secondary twinning and bent in plagioclase. F. Sub-grains and core-and-mantle  
630 microstructure with recrystallized tails (arrow) in plagioclase porphyroclast.

631 Figure 5. A. TAS diagram (Middlemost, 1994). B.  $\text{SiO}_2$  vs.  $\text{K}_2\text{O}$  diagram (Pecerillo and Taylor, 1976).  
632 C. AFM diagram (Irvine and Baragar, 1971). D, E, F. Discrimination diagrams of Frost et al. (2001).  
633 Grey dots: Guillermo lake (BA 33-17; BA 13-2-20; BA 13-3-20; BA 19-20; Dalla Salda et al., 1991;  
634 Varela et al., 2005; García-Sansegundo et al., 2009), red dots: Cordón del Serrucho and Río  
635 Ternero (SE 8-19A; Pankhurst et al., 2006; García-Sansegundo et al., 2009), green dots: Cañadón  
636 de la Mosca (Pankhurst et al., 2006; Varela et al., 2005).

637 Figure 6. A. Spider diagram normalized to NMORB (Sun and McDonough, 1989); B. REE spider  
638 diagram normalized to chondrite (Boynton, 1984). Grey dots: Guillermo lake (BA 33-17; BA 13-  
639 2-20; BA 13-3-20; BA 19-20; Varela et al., 2005; García-Sansegundo et al., 2009), red dots:  
640 Cordón del Serrucho and Río Ternero (SE 8-19A; Pankhurst et al., 2006; García-Sansegundo et  
641 al., 2009), green dots: Cañadón de la Mosca (Pankhurst et al., 2006; Varela et al., 2005).

642 Figure 7. Diagrams of Dy/Yb vs.  $\text{SiO}_2$  (A), Sr/Y vs.  $\text{Eu}/\text{Eu}^*$  (B) and Nb/Ta vs.  $\text{SiO}_2$  (C). Grey dots:  
643 Guillermo lake (BA 33-17; BA 13-2-20; BA 13-3-20; BA 19-20; Varela et al., 2005; García-  
644 Sansegundo et al., 2009), red dots: Cordón del Serrucho and Río Ternero (SE 8-19A; Pankhurst  
645 et al., 2006; García-Sansegundo et al., 2009), green dots: Cañadón de la Mosca (Pankhurst et al.,  
646 2006; Varela et al., 2005).

647 Figure 8. Nb/Yb vs. Th/Yb diagram by Pearce (2008). (OIB: Ocean Island Basalt; E-MORB:  
648 Enriched Middle Ocean Ridge Basalt; N-MORB: Normal Middle Ocean Ridge Basalt). Grey dots:  
649 Guillermo lake (BA 33-17; BA 13-2-20; BA 13-3-20; BA 19-20; Varela et al., 2005; García-  
650 Sansegundo et al., 2009), red dots: Cordón del Serrucho and Río Ternero (SE 8-19A; Pankhurst  
651 et al., 2006; García-Sansegundo et al., 2009), green dots: Cañadón de la Mosca (Pankhurst et al.,  
652 2006; Varela et al., 2005).

653 Figure 9. Granite tectonic discrimination diagram of Pearce et al. (1984). (ORG: Ocean Ridge  
654 Granites; VAG: Volcanic Arc Granites; WPG: Within Plate Granites; syn-COLG: Syncollisional  
655 Granites). Grey dots: Guillelmo lake (BA 33-17; BA 13-2-20; BA 13-3-20; BA 19-20; Varela et al.,  
656 2005; García-Sansegundo et al., 2009), red dots: Cordón del Serrucho and Río Ternerero (SE 8-19A;  
657 Pankhurst et al., 2006; García-Sansegundo et al., 2009), green dots: Cañadón de la Mosca  
658 (Pankhurst et al., 2006; Varela et al., 2005).

659 Figure 10. Microprobe image and representative profile of amphibole crystal of sample SE 8-  
660 19A, which shows no systematic variation in pressure.

661 Figure 11. Amphibole classification figure. Values correspond to tschermakite and  
662 magnesiohornblende according to fields defining by Leake et al. (1997).

663 Figure 12. Sketch map reconstructing the late Carboniferous-early Permian Gondwanide  
664 magmatic arc in northern Patagonia (ages come from Pankhurst et al., 2006; Deckart et al., 2014;  
665 Renda et al., 2019).

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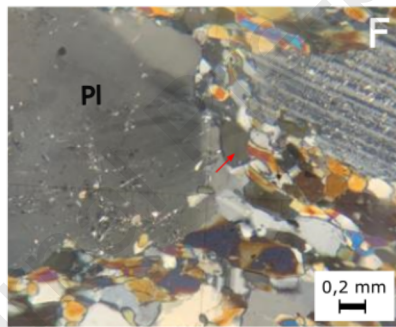
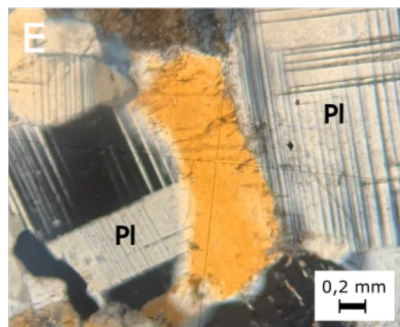
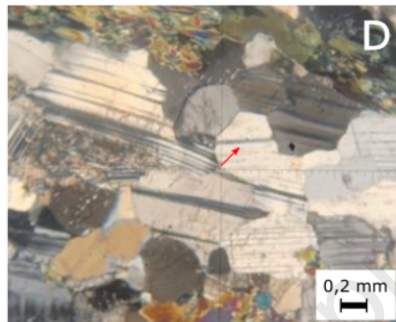
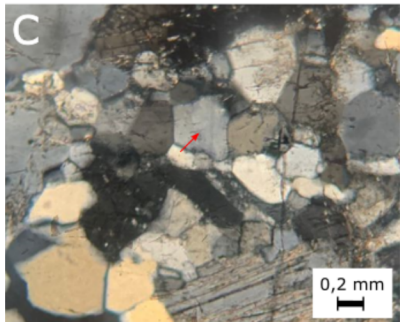
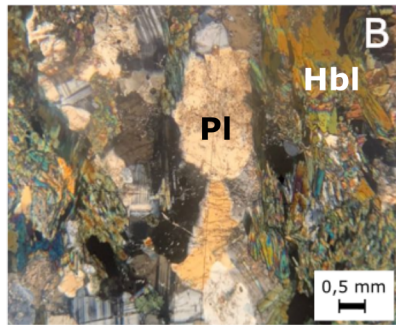
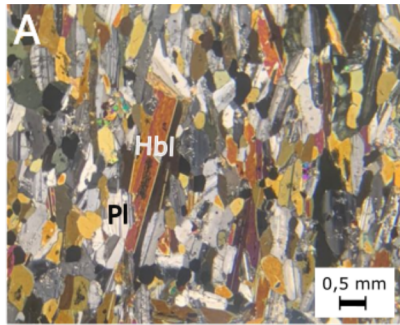
<i>Samples</i>	<i>Rock</i>	<i>Locality</i>	<i>Region</i>	<i>Age (Ma)</i>	<i>Ref</i>
<i>PIC-216</i>	Pichiñanes Granite	Sa. de los Pichiñanes	NPM	318 ± 2	1
<i>SAP 210</i>	Paso del Sapo foliated Granodiorite	Paso del Sapo	NPM	314 ± 2	1
<i>G1</i>	Paso del Sapo Plutonic Complex tonalite	Paso del Sapo	NPM	314.1 ± 2.2	4
<i>GAS 025</i>	Laguna del Toro Granodiorite	Gastre	NPM	293 ± 2	1
<i>PLA-049</i>	El Platero Tonalite	El Maiten	NPM	329 ± 4	1
<i>MAC-128</i>	Mamil Choique Formation	Sa. Mamil Choique	NPM	281 ± 2	1
<i>CUS-130</i>	El Tunel Tonalite	Río Chico	NPM	295 ± 2	1
<i>SE 8-19A</i>	Guillermo-Serrucho Plutonic Complex diorite	Morro de Shieffeld	NPC	324 ± 2	3
<i>SER-044</i>	Guillermo-Serrucho Plutonic Complex diorite	Cordón del Serrucho	NPC	330 ± 4	1
<i>MOS-043</i>	Guillermo-Serrucho Plutonic Complex diorite	Cañadón de la Mosca	NPC	323 ± 3	1
<i>BA33_17</i>	Guillermo-Serrucho Plutonic Complex diorite	Lago Guillermo	NPC	325 ± 4	3
<i>RRPS-1</i>	Chachil Plutonic Complex granite	Chachil	PCN	303 ± 2	2
<i>RA 5-18</i>	Chachil Plutonic Complex granite	Cuesta de Rahue	PCN	300 ± 2	3
<i>RA 10-18</i>	Chachil Plutonic Complex granite	Rahue	PCN	305 ± 2	3
<i>RA 48-18</i>	Chachil Plutonic Complex granite	Catán Lil creek	PCN	358 ± 2	3

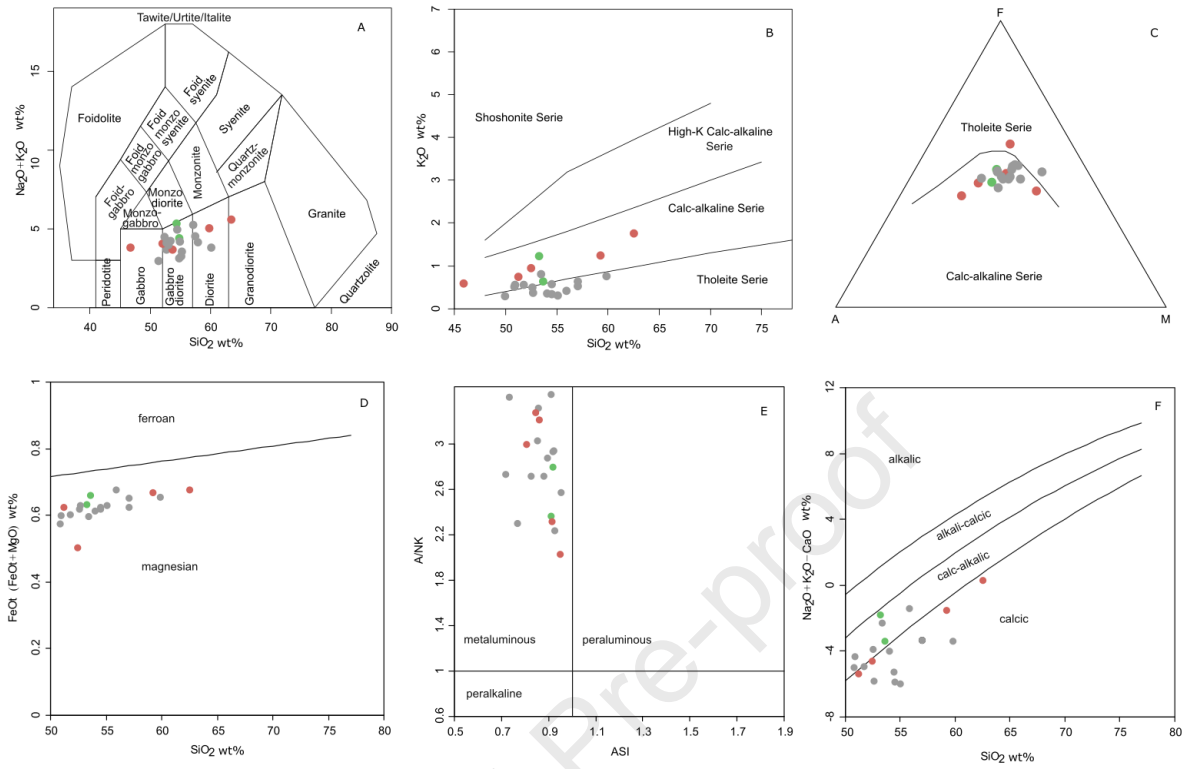
Table 1. Samples, type rock, localities and geological area and zircon U-Pb geochronological data included in the map of Figure 1. References: 1. Pankhurst et al. (2006); 2. Romero et al. (2019); 3. Oriolo et al. (2022); 4. Renda et al. (2021). (NPM: North Patagonian Massif; NPC: North Patagonian Cordillera; PCN: Precordillera Neuquina).

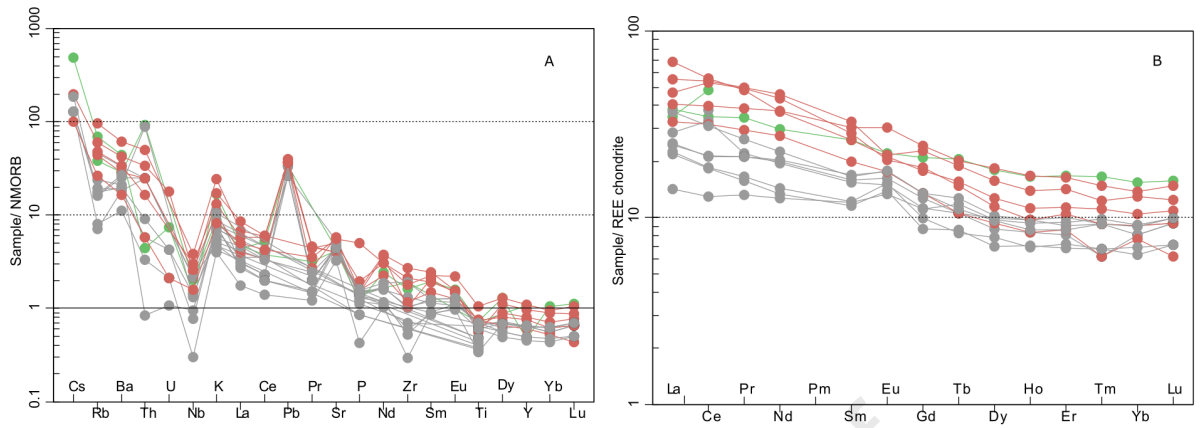


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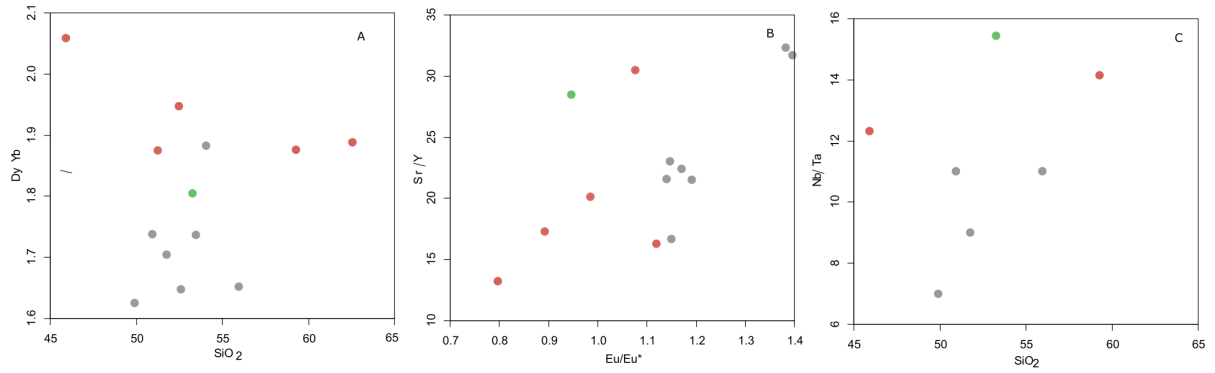


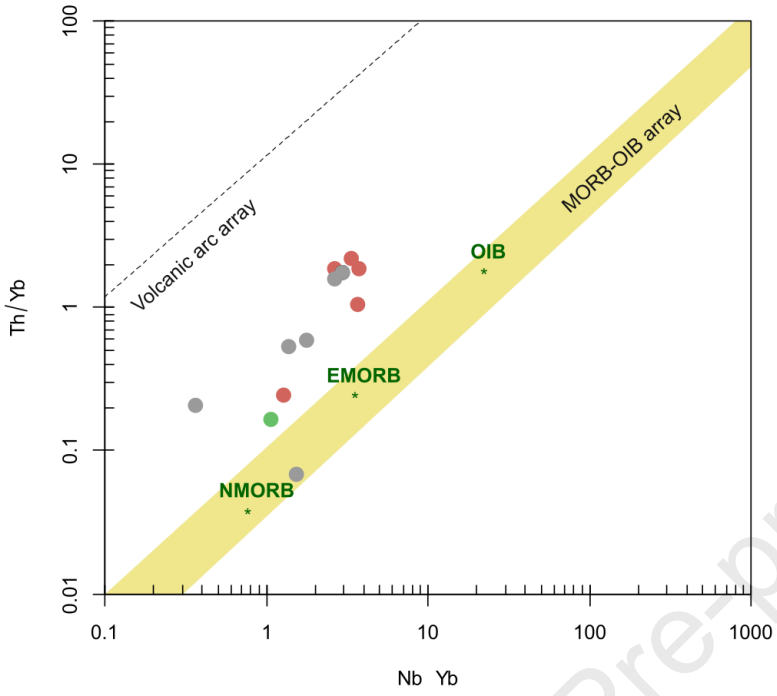


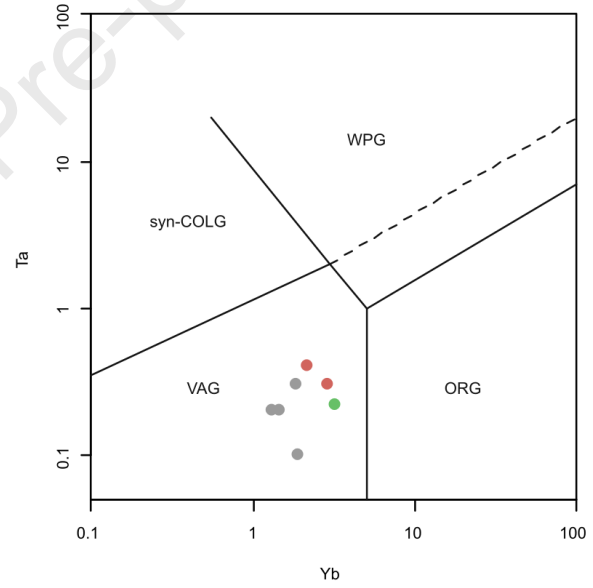
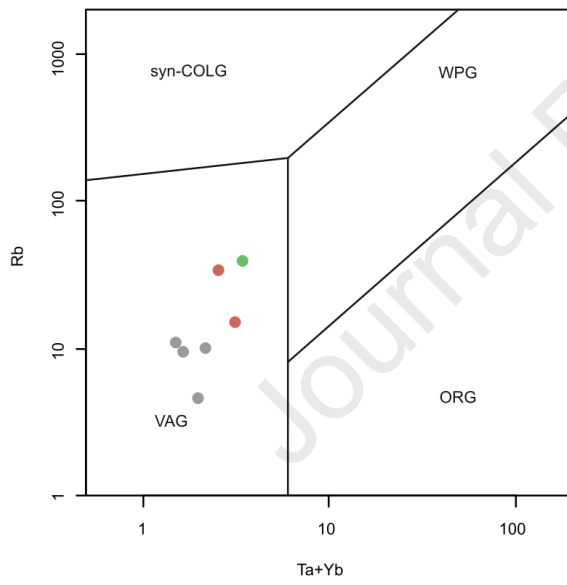
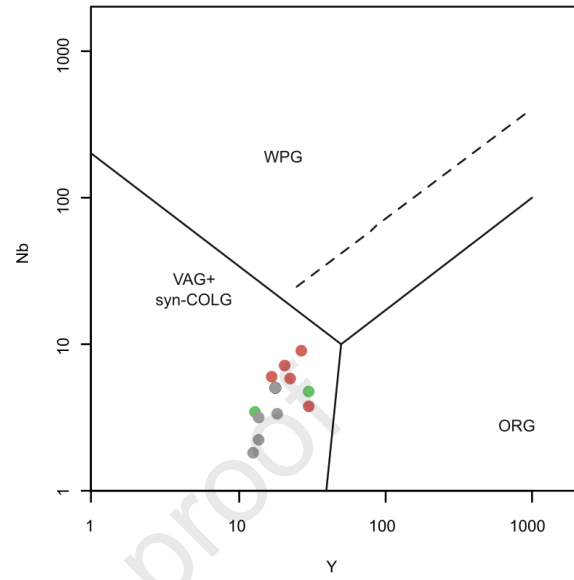
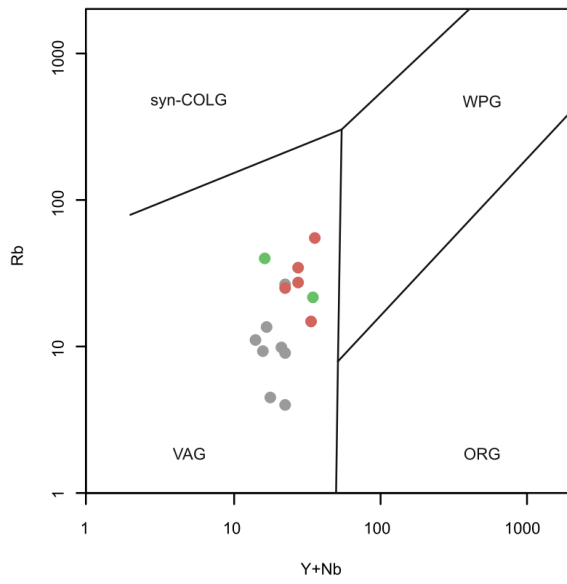


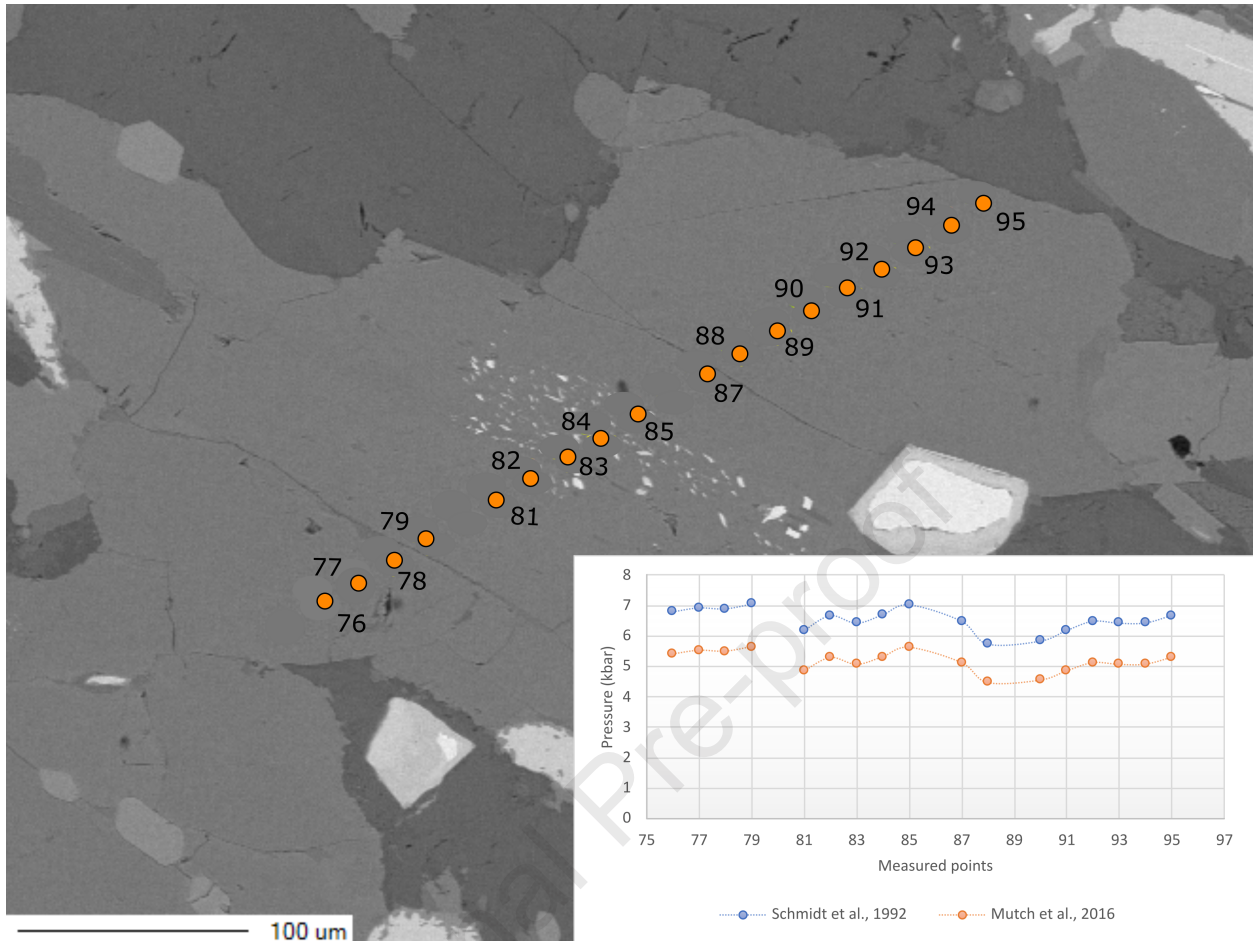


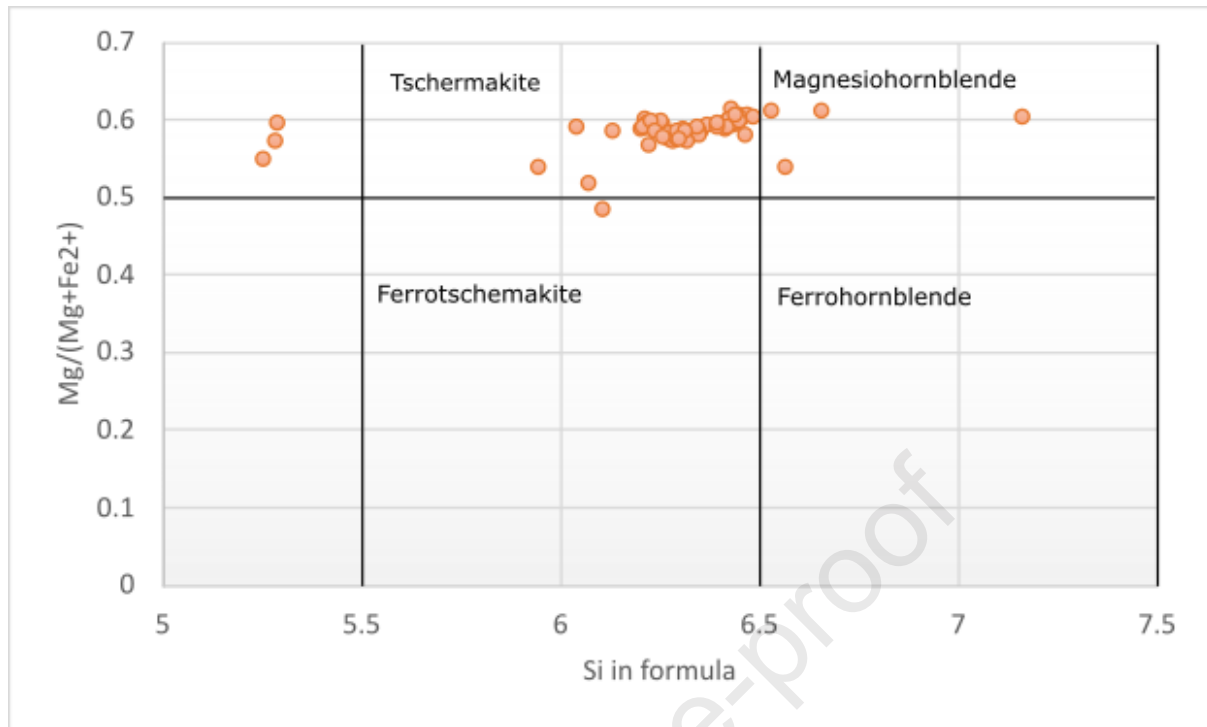




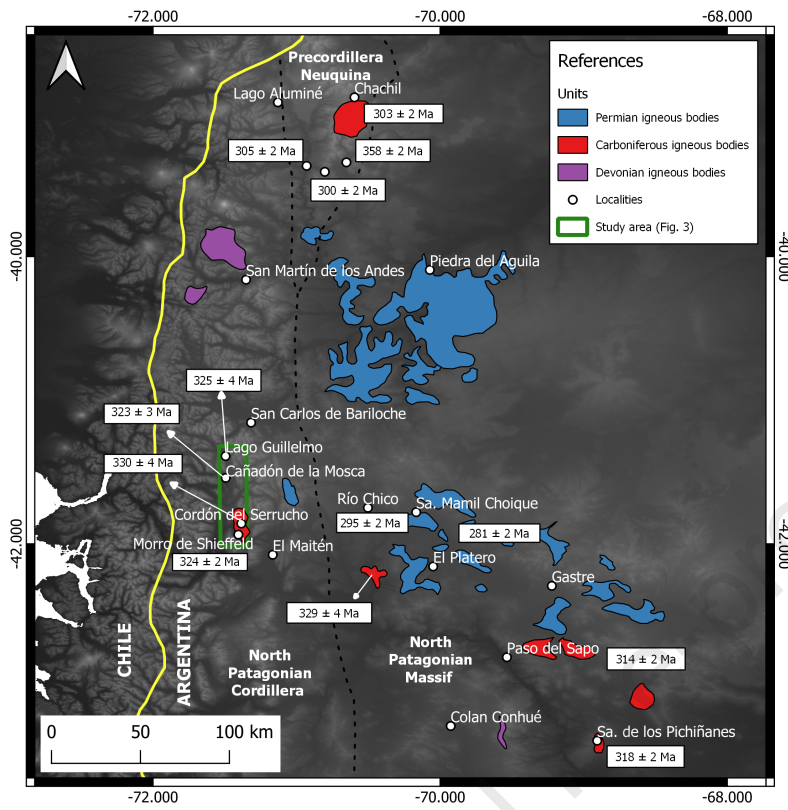


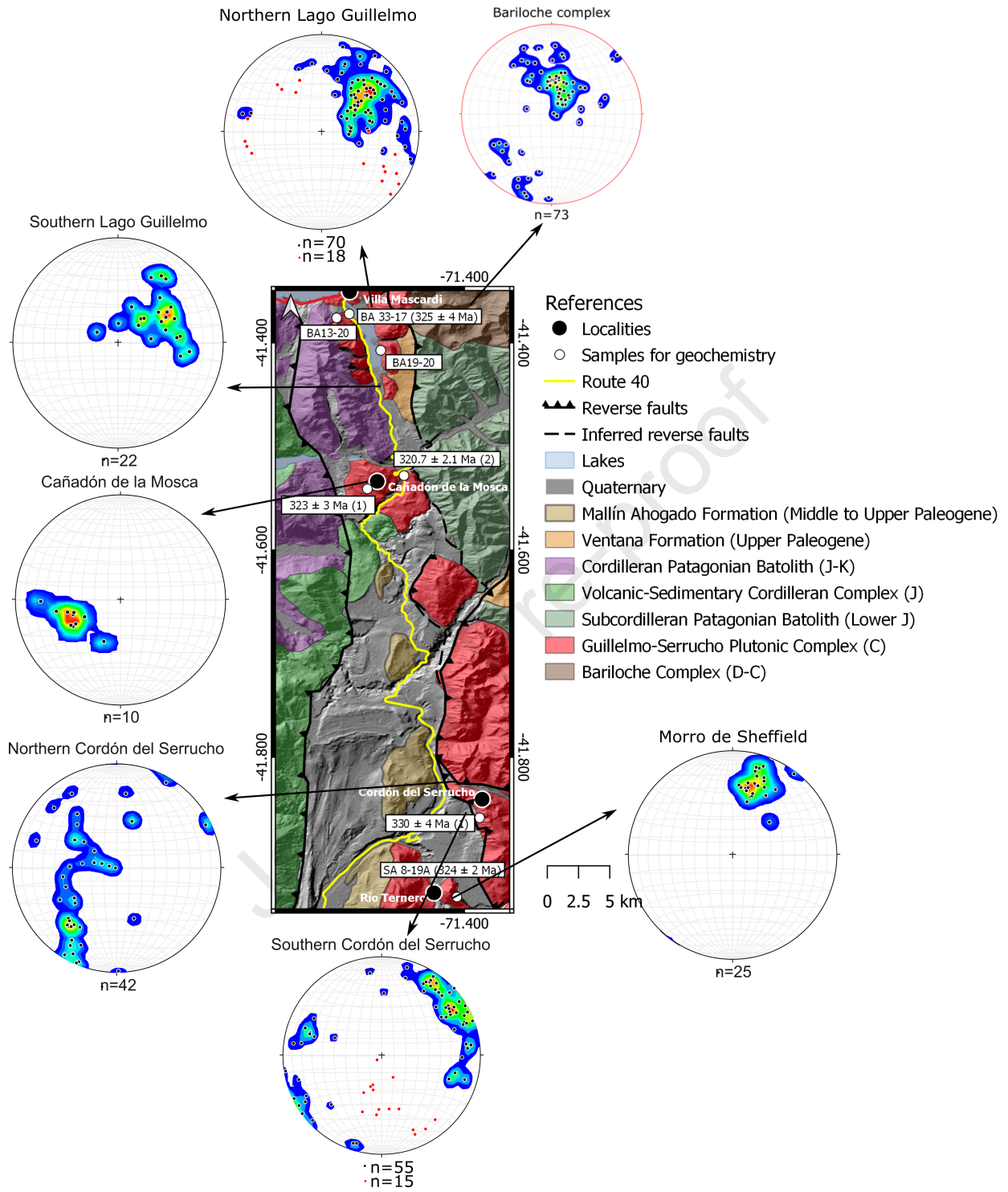














1. Basement rocks of the North Patagonian Massif are studied.
2. Guillermo-Serrucho Plutonic Complex is defined.
3. Whole-rock geochemistry and mineral chemistry data is analyzed.
4. A petrotectonic context and regional implications is discussed.
5. Sketch map reconstructing the Gondwanide magmatic arc in northern Patagonia (C-P) is presented.

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**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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