Geochronology and geochemistry of the Tabaquito batholith (Frontal Cordillera, Argentina): geodynamic implications and temporal correlations in the SW Gondwana margin

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Abstract: The Tabaquito batholith (Frontal Cordillera, western Argentina), is mainly composed of shallowly emplaced granodiorite to minor monzogranite with abundant mafic microgranular enclaves. New sensitive high-resolution ion microprobe U–Pb zircon ages of c. 337 Ma (biotite granodiorite) and c. 284 Ma (mafic dyke) along with previously published geochronological data suggest that a long-lived magmatic system formed through at least two magmatic pulses at c. 337 and c. 322 Ma with later superimposition of Permian magmatism. The Tabaquito granitoids are metaluminous, calc-alkalic and magnesium with I-type affinity. Elevated Th/Nb, Y/Nb and La/Nb ratios along with negative Nb–Ta and positive Pb anomalies are consistent with a continental arc setting. HF, Nd and Sr isotopic composition of the Tabaquito granitoids suggests that their source could result from mixing of an old felsic crustal component and a juvenile mafic to intermediate component. New geochronological and geochemical data together with published data reveal a continuous arc setting from the Carboniferous to the Permian in Argentina, and important magmatic compositional variations through time and space controlled by episodic fluctuations in the subduction angle of the oceanic plate. Reported and compiled data allow us to infer the continuity of the Carboniferous magmatic arc along the west margin of Gondwana.

Supplementary material: Detailed petrography, analytical methods and data, zircon cathodoluminescence images and supplementary figures are available at https://doi.org/10.6084/m9.figshare.c.4763993

Received 3 April 2019; revised 21 November 2019; accepted 25 November 2019

The proto-Andean margin of SW Gondwana has constituted an accretional margin from at least the earliest Ordovician until the present (Cawood 2005). It has experienced several magmatic events in the Paleozoic, which are well preserved and exposed in the Sierras Pampeanas of NW Argentina (26°–32°S latitude) (Fig. 1). Available geochronological data have allowed the identification of four main magmatic events (e.g. Pankhurst & Rapela 1998; Siegesmund et al. 2004; Dahlquist et al. 2008, 2013, 2016, 2018a; von Gosen et al. 2014; Coira et al. 2016; Casquet et al. 2018): (1) Pampean magmatism, 535–515 Ma; (2) Famatinit magmatism, 484–463 Ma; (3) Achalian magmatism, 393–366 Ma; (4) Early Gondwana magmatism, 357–322 Ma. Recently, Dahlquist et al. (2018a) have concluded that the Achalian and Early Gondwana magmatism define a long-lasting magmatic event (ranging from 379 to 322 Ma) on the pre-Andean margin of SW Gondwana between 28 and 33°S latitude, although important whole-rock and isotopic compositional variations occurred through time and space.

In the last 20 years, understanding of the petrogenesis of Pampean and Famatinit magmatism has considerably improved (e.g. Lira et al. 1997; Pankhurst & Rapela 1998; Alasino et al. 2014; von Gosen et al. 2014; Ducea et al. 2015; Larrovere et al. 2015; Otamendi et al. 2017; Casquet et al. 2018), although late Devonian and Carboniferous magmatism remains by contrast comparatively poorly understood (e.g. Dahlquist et al. 2014, 2016, 2018a).

The late Devonian–early Carboniferous geodynamical setting of the pre-Andean margin of Gondwana is particularly controversial (Alasino et al. 2012; Dahlquist et al. 2018a, and references therein) inasmuch as some researchers have argued for the lack of clear evidence for the existence of a pre-Andean magmatic arc before the late Carboniferous (c. 320 Ma; Domeier & Torsvik 2014). In agreement with this, several researchers have indicated that this was a passive margin in the Devonian (c. 420–360 Ma), based on the record of detrital zircon ages in early Carboniferous basins (e.g. Bahlburg et al. 2009; Hervé et al. 2013, 2016). Others (e.g. Willner et al. 2011, and references therein) have argued for a subduction margin followed by middle–late Devonian (c. 390 Ma) collision between Gondwana and a hypothetical terrane (Chilenia), with subsequent emplacement of early Carboniferous (c. 340 Ma) postcollisional granites in the Frontal Cordillera that remain unproven. By contrast, recent studies (Alasino et al. 2012; Dahlquist et al. 2018a)
2018a) have postulated continuous magmatism during the late Devonian and early Carboniferous characterized by marked compositional changes in space and time, probably as a consequence of fluctuations in the angle of subduction of the oceanic plate (geodynamic switching model). This resulted in coeval generation of subduction-related (calc-alkaline I-type) and retro-arc (A-type) Carboniferous magmatism (Fig. 1) (Alasino et al. 2012; Dahlquist et al. 2015) after a period of predominantly peraluminous A-type magmatism during the late Devonian (Dahlquist et al. 2018a).

The number of studies on the Carboniferous magmatism has significantly increased in the last 8 years, but they mainly focus on the intracontinental A-type magmatism of the eastern Sierras Pampeanas (Grosse et al. 2009; Dahlquist et al. 2010, 2013, 2016, 2018a; Alasino et al. 2012, 2017; Morales Cámara et al. 2017, 2018), whereas the calc-alkaline magmatism that crops out in the Frontal Cordillera and Western Sierras Pampeanas remains poorly studied (Llambías & Sato 1995; Dahlquist et al. 2015, 2018a, b). Therefore, systematic studies that characterize and discuss the petrogenesis of the calc-alkaline plutons of the Frontal Cordillera are needed to better understand the Carboniferous subduction-related magmatism.

Although the Andean subduction is one of the Earth’s main plate boundaries, a complete comprehensive geodynamic model for the palaeo-South American central western margin in Argentina does not exist. In agreement with del Rey et al. (2016), the Chilean and Argentine Frontal Andes batholiths together with the Coastal Batholith represent most of the pre-Andean orogenic cycle plutonism (the Andean orogenic cycle occurring during the early Jurassic) and its study is relevant to establish comparisons between the pre-Andean and the Andean magmatism. In the Frontal Cordillera, Carboniferous calc-alkaline magmatism was recently described in a broad-brush approach by Dahlquist et al. (2018a), but how the Carboniferous magmatism occurred along this margin previous to the Andean orogenic cycle as well as details about its petrology and geochemistry still remain unclear.

The present study aims to perform an integrated mineralogical and geochemical characterization of the Tabaquito batholith, located in the Frontal Cordillera (western Argentina), which constitutes a large outcrop (896 km²) of the early Carboniferous.
calc-alkaline magmatism (Llambías & Sato 1995; Dahlquist et al. 2018a). This magmatism remains poorly studied and is normally represented by small granitic plutons, which contrast with the large dimensions of the Tabaquito batholith. Such dimensions make the batholith an exceptional example for studying the generation of calc-alkaline magmas in the SW margin of Gondwana. Furthermore, future detailed geochronological and geochemical studies complementing those initiated here will help understand the formation of arc-related batholiths.

We present new U–Pb zircon ages along with new whole-rock compositions (major and trace elements), Nd and Sr isotopes, mineral chemistry of the major mineral assemblage, and P–T estimations. These data are integrated with those reported by Llambías & Sato (1995) and Dahlquist et al. (2018a) as a first step to understand the petrogenesis of the batholith. The results are compared with available chemical data for other Carboniferous subduction-related plutons of Argentina and Chile to give a wider view of the subduction-related granitic magmatism at the pre-Andean margin of SW Gondwana during the Carboniferous.

Geological setting: the Frontal Cordillera and Tabaquito batholith

Frontal Cordillera

The Frontal Cordillera is a morphostructural province involved in the Andean orogeny, located to the west of the Precordillera and extending between 27 and 34°45′S latitude in Argentina, as well as between 27 and 31°S latitude in Chile (Caminos 1979; Maksaev et al. 2014; Sato et al. 2015) (Fig. 1).

The stratigraphic section of the Frontal Cordillera can be divided into three major representative units (Sato et al. 2015, and references therein), as follows.

1. Pre-Carboniferous basement units that consist of Mesoproterozoic orthogneisses, Ediacaran to Cambrian rock sequences affected by Devonian high-pressure metamorphism, and Ordovician and Devonian sedimentary rocks (Chinguillos and Ciénaga del Medio groups) with intrusions of Devonian plutonic rocks.

2. Carboniferous to Triassic sedimentary and igneous sequences. Among the most notable are the Cerro Agua Negra formation, the Colangüil batholith, and volcanic and plutonic rocks of the Chinguillos group. The youngest rocks of the last are associated with an extensional environment.

3. Rock sequences assigned to the Andean orogeny that mainly consist of early Jurassic to Neogene sedimentary and volcanic rocks.

The Carboniferous magmatism of the Frontal Cordillera and Western Sierras Pampeanas (Fig. 1) has long been considered part of a probable Carboniferous magmatic arc (e.g. Llambías & Sato 1995; Alasino et al. 2012; Dahlquist et al. 2015, 2018a). This magmatism, in the area between 28 and 30°S latitude, is represented by isolated granitic bodies that occur as scattered plutons of variable size throughout the region (Fig. 1). These plutons are poorly studied although new geochronological data together with a brief geochemical characterization of most of the plutons have been recently reported in a regional or broad-brush approach study (Dahlquist et al. 2018a). The plutons that belong to this arc-related magmatism are the following.

1. The Potrerillos pluton (353 ± 2 Ma; Dahlquist et al. 2018a) is an elliptical intrusive body of c. 78 km² (south of Sierra del Toro Negro; Fig. 1) mainly formed of an amphibole–biotite quartz-diorite with mafic microgranular enclaves and a porphyritic biotite granodiorite (Frigerio et al. 2012; Dahlquist et al. 2018a).

2. The Las Tunas pluton (324 ± 6 Ma by K–Ar method; Caminos 1972) is a small granitic pluton located in the Frontal Cordillera to the west of Sierra del Toro Negro (Fig. 1).

3. The Rio Bonete stock (342 ± 5 Ma; Dahlquist et al. 2018a) is an intrusive body of c. 2 km³ in the northeastern part of the Precordillera and south of Sierra del Toro Negro (Fig. 1). It consists of two facies, one represented by a dark equigranular medium-grained gabbro and the other by a coarse-grained porphyritic monzonite.

4. The Veladero stock (342 ± 2 Ma; Dahlquist et al. 2018a) is an intrusive body of c. 9 km³ in the eastern flank of the Precordillera and the western part of the Western Sierras Pampeanas (Sierra de Umango) (Fig. 1). This granitic stock is made of quartz-poor monzogranite, quartz-monzonite, monzodiorite and syenogranite.

5. The Guandacolinos pluton (357 ± 2 Ma; Dahlquist et al. 2018a) crops out over an area of 24 km² in the western flank of the Sierra de Umango (Fig. 1) and is made of monzogranite to granodiorite with biotite and scarce amphibole.

6. The Tabaquito batholith (322 ± 5 Ma; Dahlquist et al. 2018a) is located in the Frontal Cordillera (Fig. 1) and is described below. This batholith, which is the subject of this study, is located in the Frontal Cordillera north of the Colangüil batholith (San Juan province; Fig. 1). The term ‘Colangüil batholith’ was first coined by Quartino & Zardini (1967) in reference to the various plutonic acid rocks that crop out between the Santa Rosa and Agua Negra creeks, whereby the so-called ‘Tabaquito pluton’ was considered part of the batholith (Llambías & Sato 1995). According to previous studies (Llambías & Sato 1990, 1995; Sato et al. 2015) the lithostratigraphy of the Colangüil region consists of a late Carboniferous granodiorite to monzogranite pluton (‘Tabaquito pluton’, 322 ± 5 Ma; Dahlquist et al. 2018a) and several Permian granodioritic and granitic plutons (252–279 Ma; Sato et al. 2015). Consequently, although the ‘Tabaquito pluton’ was first considered part of the Colangüil batholith, its Carboniferous age precludes this possibility. The country rocks of the various igneous bodies are metasedimentary rocks of the Chinguillos and Cerro Agua Negra formations that consist of marine siliciclastic sequences of Devonian and Carboniferous to Permian age, respectively (Sato et al. 2015).

Field characteristics of the Tabaquito batholith

The Tabaquito igneous body crops out over an area of about 896 km² to the north of the Colangüil batholith (Fig. 2). We propose to use the term Tabaquito batholith instead of pluton because of its significant dimensions (>200 km²; see batholith definition in Chapter 14 of Pitcher 1993) and the difference in age between samples found in this study as discussed in the ‘Geochronological implications’ section. The batholith is mostly covered by Quaternary sedimentary deposits and contacts between rocks are hard to find in this area owing to strong erosion under high mountain weather conditions, as most of the batholith crops out above 3500 m a.s.l. (metres above sea level). Thus, a detailed geochronological study is essential to establish the sequence of emplacement.

Our field studies confirm that the batholith is mainly formed of equigranular medium-grained grey granodiorites (Fig. 3a) that can be locally porphyritic with 70 vol% phenocrysts (0.6–5 mm) and 30 vol% matrix (<0.5 mm), although minor monzogranite compositions have also been reported by Llambías & Sato (1995). Field relations between equigranular and porphyritic varieties could not be observed. Their main mineral assemblage is represented by plagioclase + quartz + alkali feldspar + biotite + opaque minerals ± amphibole (see detailed petrography in supplementary file S1). They contain abundant biotite- and amphibole-bearing mafic microgranular enclaves of centimetre to decimetre scale (Fig. 3a). Although the biotite-rich and amphibole-poor enclaves are the most common (Llambías & Sato 1995), there also exist abundant
biotite–amphibole-rich enclaves with the common occurrence of amphibole clots, which are described here for the first time (see detailed petrography in supplementary file S1).

The batholith intrudes metasedimentary rocks of the Chinguillos Formation of Devonian age (Figs 2 and 3b, c) and it is intruded to the south by the El Fierro pluton, which belongs to the Los Puentes granite, with biotite/whole-rock Rb–Sr and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) U–Pb ages that vary between 257 ± 1 and 253 ± 2 Ma (Llambías & Sato 1995; Sato et al. 2015). However, our fieldwork in the southern part of the batholith reveals the existence of metre-size small outcrops of a fine-grained leucogranite (Fig. 3d) that consists of quartz (38 vol%), alkali feldspar (33 vol%), plagioclase (27 vol%) and biotite (2 vol%), and outcrops of a coarse-grained porphyritic
granite (Figs 2 and 3e) made of alkali feldspar (35–38 vol%), quartz (34–38 vol%), plagioclase (24–27 vol%), biotite (2–4 vol%) and muscovite (<1.5 vol%), which have not been studied yet. The coarse-grained porphyritic granite is in turn cut by aplitic dykes (Fig. 3f). Elsewhere, the eastern and western limits are truncated by Neogene Andean tectonic structures as reported by Sato et al. (2015). The batholith is also intruded by ‘radial’ dyke swarms of mainly andesitic composition with subordinate dacitic to rhyolitic compositions, which in turn are crosscut by north–south mainly rhyolitic dykes probably related to the Permian magmatism of the Choiyoi group (Llambías & Sato 1995). The middle–late Mississippian age of the Tabaquito batholith was first estimated by Rb–Sr isochrons (326–329 Ma; Llambías & Sato 1995) and subsequently corroborated by LA-MC (multicollector)-ICP-MS U–Pb zircon dating (322 ± 5 Ma; Dahlquist et al. 2018a).

Samples and methods
For this study, we collected nine samples from the Tabaquito batholith (five from the host granodiorite, one mafic enclave, one mafic dyke and two felsic dykes). Mineral compositions were determined in three samples (two host equigranular amphibole-bearing granodiorites and one mafic enclave). Whole-rock major and trace element compositions were determined for the whole set of samples, and three samples (TAB-11, TAB-24 and TAB-32) have been also analysed for Nd and Sr isotopes. For U–Pb zircon dating,
zircon grains were separated from one biotite-bearing sample from the south of the batholith (TAB-24) and one mafic dyke (TAB-40) from the north. Detailed information about the analytical procedures of the methods used are given in the supplementary material (Text S1 and Table S1). This study also integrates previous published data (geochemical, geochronological and isotope data) from Llambías & Sato (1995) and Dahlquist et al. (2018a).

Mineral chemistry

Feldspars

Plagioclase in the granodiorite is essentially andesine ($\text{An}_{30-49}$; Fig. 4a) showing compositional zoning with cores richer in calcium ($\text{An}_{42-49}$) than rims ($\text{An}_{30-37}$) (Table 1). The composition of alkali feldspar is less variable and ranges from $\text{Or}_{89}$ to $\text{Or}_{96}$ (Fig. 4a and supplementary material Table S2).

Plagioclase from the mafic enclaves is also andesine (Fig. 4a) with compositions similar to those of the granodiorite. Phenocrysts are characterized by compositions that vary between $\text{An}_{42}$ and $\text{An}_{46}$ with a poikilitic outer rim of oligoclase composition ($\text{An}_{21-25}$) (supplementary material Table S2). They also show complex zoning with patches of oligoclase composition ($\text{An}_{32}$). Matrix plagioclase has cores of andesine composition ($\text{An}_{42-46}$) and rims of oligoclase composition ($\text{An}_{21-31}$) (supplementary material Table S2).

Biotite

Trioctahedral mica from both the granodiorite and the enclaves is annite (Fig. 4b) with very uniform Mg/(Mg + Fe$^{2+}$) of 0.46–0.52 (supplementary material Table S2). Li contents calculated by the method described by Tischendorf et al. (2004) are low (0.05–0.06 a.p.f.u.) (Table 2). F and Cl contents are very low, with F being slightly higher than Cl with values of 0.04–0.15 a.p.f.u. and 0.02–0.05 a.p.f.u. respectively (supplementary material Table S2).

In the MgO–FeO–Al$_2$O$_3$ diagram from Abdel-Rahman (1994) (Fig. 4c), all analyses plot in the field of calc-alkaline granitoids, which is in accordance with the expected I-type affinity of these magmas.

![Fig. 4. Composition of feldspar, biotite and amphibole from the Tabaquito granitoids. (a) Feldspar composition. An–Ab–Or diagram (data in mol%). (b) Biotite composition. FeAl v. MgLi diagram (after Tischendorf et al. 2007). Open circles represent end-member compositions that are indicated by abbreviations. (c) Biotite composition. MgO–FeO–Al$_2$O$_3$ diagram (after Abdel-Rahman 1994). Data in wt%. (d) Calcic amphibole composition. Mg number v. Si diagram. Ab, albite; An, anorthite; Ann, annite; Eas, eastonite; Hyp-mus, hyper-muscovite; Mus, muscovite; Mont, montmorillonite; Phl, phlogopite; Pol, polythionite; Or, orthoclase; Sid, siderophyllite; Tri, triphylite.](image-url)
| Sample TAB-24 |  |  |  |
|---|---|---|---|
| Sample TAB-40 |  |  |  |

| Sample | e,p,osc | 446 | 55 | 0.12 | 20.3 | 1.1E−3 | 1.95 | 18.48 | 0.2 | 0.0700 | 0.0042 | 18.84 | 0.1717 | 0.0546 | 0.0049 | 0.400 | 0.0364 | 0.0531 | 0.0005 | 0.10 | 333 | 3 | 396 | 203 +16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Error in Temora reference zircon calibration was 0.36% for the analytical session. Errors are 1σ.
### Table 2. Whole-rock compositions for the Tabaquito granitoids and dykes

| Rock type | Grd | Grd | Grd | Grd | MME | Grd | FD | MD | FD |
|-----------|-----|-----|-----|-----|-----|-----|----|----|----|
| Latitude (S) | 28°55'43.3" | 28°56'1.1" | 29°06'43.9" | 29°08'39.3" | 29°08'39.3" | 29°07'48.2" | 29°07'46.9" | 28°55'10.7" | 28°55'9.1" |
| Longitude (W) | 69°08'47.1" | 69°08'29" | 69°18'52" | 69°21'10.5" | 69°21'10.5" | 69°20'35.3" | 69°18'26.6" | 69°06'45.9" | 69°06'20" |
| Sample | TAB-11 | TAB-20 | TAB-24 | TAB-31 | TAB-32 | TAB-34 | TAB-35 | TAB-40 | TAB-41 |

**Major elements (wt%)**

- **SiO₂**: 66.02, 65.63, 66.92, 66.04, 55.04, 65.05, 73.88, 55.84, 68.35
- **TiO₂**: 0.65, 0.59, 0.56, 0.64, 0.95, 0.67, 0.13, 0.78, 0.47
- **Al₂O₃**: 15.93, 15.68, 15.22, 14.83, 15.80, 15.91, 15.91, 18.31, 15.33
- **FeO**: 4.28, 3.83, 3.67, 4.46, 7.66, 4.09, 0.78, 7.11, 2.91
- **MnO**: 0.07, 0.06, 0.06, 0.08, 0.21, 0.06, 0.02, 0.15, 0.05
- **MgO**: 1.70, 1.69, 1.59, 2.26, 6.04, 2.05, 0.78, 3.49, 1.21
- **CaO**: 3.77, 3.66, 3.14, 3.05, 3.30, 3.08, 3.98, 2.98, 3.76
- **Na₂O**: 3.15, 3.05, 2.92, 3.05, 3.30, 3.08, 3.98, 3.98, 3.88
- **K₂O**: 3.27, 3.64, 3.79, 3.05, 3.30, 3.08, 3.98, 3.98, 3.88
- **P₂O₅**: 0.17, 0.15, 0.15, 0.17, 0.19, 0.17, 0.19, 0.24, 0.13
- **LOI**: 0.80, 1.40, 1.30, 1.20, 1.30, 1.20, 0.72, 2.97, 1.83
- **Total**: 99.81, 99.38, 99.32, 99.22, 98.83, 99.28, 98.83, 100.01, 99.48

**Trace elements (ppm)**

- **Cs**: 5.8, 4.7, 6.8, 9.8, 8.4, 13.3, 10.1, 2.9, 3.1
- **Rb**: 124, 154, 157, 191, 162, 168, 336.7, 82.7, 94.5
- **Sr**: 361, 332, 233, 290, 230, 330, 44.8, 587, 359.2
- **Ba**: 704, 629, 464, 616, 353, 593, 315, 1048, 630
- **La**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **Ce**: 73.9, 75.1, 60.3, 65.1, 66.1, 64.8, 54.3, 49.2, 46.4
- **Pr**: 8.5, 8.4, 7.0, 4.6, 0.7, 1.9, 1.13, 1.03, 0.83
- **Nd**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **Sm**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **Eu**: 0.72, 0.69, 0.70, 0.66, 0.56, 0.67, 0.78, 0.93, 0.71
- **Gd**: 0.75, 0.85, 0.87, 0.72, 0.19, 0.72, 0.83, 0.93, 0.83
- **Tb**: 0.75, 0.85, 0.87, 0.72, 0.19, 0.72, 0.83, 0.93, 0.83
- **Yb**: 0.75, 0.85, 0.87, 0.72, 0.19, 0.72, 0.83, 0.93, 0.83
- **Y**: 0.75, 0.85, 0.87, 0.72, 0.19, 0.72, 0.83, 0.93, 0.83
- **Nb**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **Zr**: 73.9, 75.1, 60.3, 65.1, 66.1, 64.8, 54.3, 49.2, 46.4
- **Hf**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **Ta**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **Sc**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **V**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **Ga**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **Pb**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **(La/Lu)N**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **(Th/Ta)N**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **Eu/Eu***: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **87Rb/86Sr**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **87Sr/86Sr**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **147Sm/144Nd**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **143Nd/144Nd**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2
- **εNd**: 36, 38.6, 30.5, 32.0, 25.0, 33.2, 21.2, 21.8, 25.2

*FD, felsic dike; Grd, granodiorite; MD, mafic dike; MME, mafic microgranular enclave. LOI, loss on ignition.*
Amphibole

Amphibole in the granodiorite is magnesio-hornblende (nomenclature after Leake 1997; Fig. 4d) and in the mafic clots it shows alteration to actinolite. Analysed amphibole from the mafic clots and single crystals has Mg/(Mg + Fe²⁺) of 0.57–0.74, low Ti (0.01–0.18 a.p.f.u.) and very low F and Cl contents (0–0.15 a.p.f.u. and 0.01–0.05 a.p.f.u. respectively). It should be noted that the single crystals have higher Ti (0.09–0.18 a.p.f.u.) and lower Mg/(Mg + Fe²⁺) (0.57–0.60) than amphibole from the mafic clots. It is noteworthy that analyses from sample TAB-11, collected in the northern part of the batholith, have higher Mg/(Mg + Fe²⁺) than those from sample TAB-34 (Fig. 4d and supplementary material Table S2) collected in the southern sector.

Amphibole from the quartz-dioritic enclaves is also magnesio-hornblende (Fig. 4d) although it shows higher alteration to actinolite in the amphibole clots. Amphibole grains from the clots are chemically similar to those of the clots in the granodiorite, with Mg/(Mg + Fe²⁺) of 0.62–0.72, low Ti (0.01–0.10 a.p.f.u.) and very low F and Cl contents (≤0.07 a.p.f.u. and 0.01–0.02 a.p.f.u. respectively). Amphibole grains from the matrix and those included in plagioclase phenocrysts are similar in composition with Mg/(Mg + Fe²⁺) of 0.57–0.67, Ti 0.07–0.18 a.p.f.u., F 0–0.15 a.p.f.u. and Cl 0.01–0.03 a.p.f.u. (supplementary material Table S2).

Epidote

Primary epidote from sample TAB-34 (granodiorite) has pistacite content (Ps (%) = Fe³⁺/(Fe³⁺ + Al) × 100) of 23–28 and very low TiO₂ content (<0.1 wt%) (supplementary material Table S2), which are typical values of magmatic epidote (Evans & Vance 1987; Vyhnal et al. 1991 ; Dahlquist 2001).

U–Pb zircon dating

In this section we present new U–Pb zircon data for samples TAB-24 and TAB-40 (Table 1).

TAB-24

More than 100 zircon grains from sample TAB-24 (porphyritic biotite-bearing granodiorite from the southern sector of the batholith) were studied by cathodoluminescence (CL), from which 12 grains were analysed by sensitive high-resolution ion microprobe (SHRIMP). The analysed zircons tend to have relatively elevated common lead. The studied zircons are mainly euhedral, prismatic with bipyramidal terminations (supplementary file S2), although scarce fragmented and rounded grains are also present. Under the CL microscope most zircons show well-developed oscillatory zoning (supplementary file S2) but sector zoning and homogeneous textures have been also recognized. The analyses were carried out mainly on rims or edge zones of selected grains to obtain the crystallization age (Table 1). The whole set of analysed zircons yielded a 206Pb/238U age of 337 ± 2 Ma (n = 12, MSWD = 0.022; Fig. 5a) that is the same as the 206Pb/238U age obtained when we use only the most concordant analyses (338 ± 2 Ma, discordance <10%, n = 9, MSWD = 0.00069). Therefore, we consider the age of 337 ± 2 Ma as the crystallization age of this sample, which is older than the previous U–Pb age of 322 ± 4 Ma reported by Dahlquist et al. (2018a) in the northern part of the batholith.

TAB-40

Thirty-two zircon grains from sample TAB-40 (a north–south mafic dyke from the north of the batholith) were studied by CL, from which 12 grains were analysed by SHRIMP (Table 1). The studied zircons are mostly rounded and fragmented grains with sector and oscillatory zoning (supplementary file S3). Homogeneous bright and dark zones are also common (supplementary file S3). Four U–Pb determinations made on four of the 12 analysed zircon grains yielded a 206Pb/238U age of 284 ± 4 Ma (MSWD = 0.067; Fig. 5b) that may represent the crystallization age of the dyke. However, seven U–Pb concordant determinations made on seven zircons gave a 206Pb/238U age of 336 ± 3 Ma (MSWD = 0.0052; Fig. 5b) that overlaps with the crystallization age of sample TAB-24.

Whole-rock chemistry

In this section we use new major and trace element data for granitoids and dykes (Table 2) along with data from Llambías & Sato (1995) to characterize the magmatism of the Tabaquito batholith.

Granodiorites and monzogranites that form the batholith are magnesian (FeO/(MgO + FeO) by weight = 0.66–0.75), calc-alkaline (MALI = Na₂O + K₂O – CaO by weight = 2.65–5.2) and metaluminous to weakly peraluminous (alumina saturation index, ASI = 1.10–1.12) (Fig. 6a–c), with 65.5–70.5 wt% SiO₂, 14.5–15.9 wt% Al₂O₃, 0.39–0.69 wt% TiO₂, 2.69–4.46 wt% FeO and 1.11–2.26 wt% MgO (Table 2). The studied quartz-diorite enclave is strongly magnesian (Fe-number = 0.56), alkali-calcic (MALI = 1.12) and metaluminous (ASI = 0.86) (Fig. 6a–c). Both the Tabaquito granitoids and the enclave are potassium-rich rocks (3.08–4.32 wt% K₂O; Fig. 6d).

The three dyke samples plot in the fields of basaltic trachyandesite (TAB-40), dacite (TAB-41) and rhyolite (TAB-23) of the total
Fig. 6. Whole-rock composition of the Tabaquito granitoids. (a) Fe-number v. SiO$_2$ diagram. Cordilleran granitoid field (light blue) after Frost et al. (2001). (b) MALI-index v. SiO$_2$ diagram after Frost et al. (2001). (c) Molar alumina saturation index v. Al$_2$O$_3/(Na_2O$+K$_2$O). (d) SiO$_2$ v. K$_2$O diagram. (e) TAS (total alkalis–silica) diagram. Data for the Carboniferous subduction-related magmatism of Argentina (Frontal Cordillera and Western Sierras Pampeanas) and Chile are taken from Nasi et al. (1985), Parada et al. (1999) and Dahlquist et al. (2018a).
alkalis–silica (TAS) diagram (Fig. 6e). Furthermore, as sample TAB-40 has Na₂O – 2 ≤ K₂O, it is additionally classified as a shoshonite. They are high-K, magnesian to ferroan (FeO/[(MgO + FeO)] by weight = 0.67–0.94), calc-alkaline to alkali-calcic (MALI = 0.93–8.58) and peraluminous (ASI = 1.03–1.18) (Fig. 6a–c).

In Harker diagrams, the Tabaquito granitoids show negative correlations between silica and FeO, MgO, TiO₂, Al₂O₃ and P₂O₅ (supplementary material, Fig. 1), whereas Na₂O is nearly constant and CaO shows higher dispersion, although with a tendency to decrease as silica increases (supplementary material, Fig. 1).

Chondrite-normalized REE patterns of the Tabaquito granitoids show a moderately negative slope (LaN/LuN = 6.74–10.14) with a small negative Eu anomaly (Eu/Eu* = 0.62–0.79), and they are nearly flat from Ho to Lu (Fig. 7a). The enclave shows a similar pattern (LaN/LuN = 4.18; Eu/Eu* = 0.68) but with lower La and elements showing negative Ba, Nb anomalies along with a positive Pb anomaly (Fig. 7b). The negative Th anomaly of the enclave, which contrasts with the relatively high Th values of the granodiorites, should be noted (Fig. 7b). The studied samples

![Fig. 7. Chondrite-normalized REE and Silicate Earth-normalized trace element diagrams. Normalization values after McDonough & Sun (1995).](image-url)
plot within the compositional range of the Argentine arc-related Carboniferous magmatism (Fig. 7b) and strongly contrast with the REE pattern and spider-multielement diagram reported for the Carboniferous A-type magmatism (e.g. Dahlquist et al. 2010, 2018a).

REE and trace elements compositions of the dykes are similar to those described for the Tabaquito granitoids although the dacite dyke (TAB-41) has slightly lower values of REE (Fig. 7).

Nd and Sr isotopes

Sr and Nd isotope compositions of the studied samples (TAB-11, TAB-24 and TAB-32) are listed in Table 2. Initial radiogenic isotope ratios were calculated at crystallization ages (322 and 337 Ma; Dahlquist et al. 2018a, and this study). Nd model ages (TDM) were calculated according to the expression derived by DePaolo (1981). The 143Sm/144Nd ratios in the analysed samples are below the threshold value of 0.165, above which calculated model ages tend to be unreliable (see discussion by Stern 2002).

The studied samples present εNd values that range between −1.61 and −2.38, along with Nd model ages that vary between 1091 and 1113 Ma. The Sr parameters of the studied samples (Sr/Sr₀ = 0.7053–0.7056) are in the range of those calculated from the Llambías & Sato (1995) data (Sr/Sr₀ = 0.7039–0.7071), except for one sample that has a clearly higher value (Sr/Sr₀ = 0.7095). It should be noted that isotope values of the amphibole-bearing granodiorite (TAB-11) and biotite-bearing porphyritic granodiorite (TAB-24) as well as those of the enclave (TAB-32) are nearly the same although the biotite-bearing porphyritic granodiorite has slightly lower εNd, (Table 2).

P–T conditions

Crystallization conditions for rocks of the Tabaquito batholith have been determined using amphibole-only and amphibole–plagioclase thermobarometric expressions (Schmidt 1992; Holland & Blundy 1994; Ridolfi & Renzulli 2012; Molina et al. 2015; Mutch et al. 2016; Putirka 2016). A summary of the calculated amphibole-only and amphibole–plagioclase P–T conditions for samples TAB-11 (north of the batholith), TAB-32 and TAB-34 (south of the batholith) is presented in Table 3. Temperatures calculated with the diverse amphibole-only calibrations are similar (range 705–810°C; Table 3), being virtually the same when considering the error of each calibration.

Al-in-amphibole pressure estimates for amphibole from the amphibole clots and single crystals in granodiorites (TAB-11 and TAB-34) vary between 1.4 and 3.1 kbar for the different calibrations (Table 3). The pressure calculated with the plagioclase–amphibole barometer of Molina et al. (2015) gave 1.7 ± 0.6 kbar at 750°C (Table 3). Therefore, the pressure estimates for rim compositions of the single crystals and for amphibole from the clots (<2.5 kbar; Table 3) indicate a shallow emplacement of these magmas.

Temperatures for amphibole from the clots calculated with the amphibole-only thermometers range from 720 to 785°C (Table 3). In the case of single crystals, temperatures vary between 738 and 810°C. Temperatures calculated at 2 kbar with the amphibole–plagioclase thermometer (Holland & Blundy 1994) for the

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Fig. 8. Relationships of trace element ratios of the Tabaquito granitoids. (a) (Th/Nb)ₕ v. (Y/Nb)ₕ. (b) (Th/Nb)ₕ v. (La/Nb)ₕ. Normalization values after McDonough & Sun (1995). Compositional fields after Moreno et al. (2016). CA, continental arcs; CC, continental crust; IA, island arcs; OIB, ocean island basalts; Sh, shoshonites; Sub, subduction-related magmatic suites.
individual crystals are 754 ± 30°C (Ed–Q–Tr–Ab expression) and 767 ± 20°C (Ed–Ab–Rich–An expression) (Table 3), which match those of the amphibole-only thermometers on the other hand. In the case of amphibole from the clots the Ed–Q–Tr–Ab thermometer gives temperatures that are excessively low, sometimes being more than 150°C lower than those obtained with the Ed–Ab–Rich–An thermometer, which are closer to those of the amphibole-only thermometer. Consequently, we have considered only the Ed–Ab–Rich–An thermometer. This could be a consequence of these clots not being in equilibrium with quartz, because for these analyses unrealistic pressures have been obtained with the barometer of Molina et al. (2015), which works better for mineral assemblages in equilibrium with quartz and/or clinopyroxene. Consequently, we have considered only the Ed–Ab–Rich–An thermometer, which gives temperatures of 692–776°C for plagioclase compositions of An30–37 and 720–825°C for An42–49 (Table 3).

The mafic enclaves (sample TAB-32) has pressures of 0.8–3.3 kbar calculated with the different barometers (Table 3). Temperatures calculated with the amphibole-only thermometers are similar for amphibole grains from the matrix, the clots and those included in plagioclase phenocrysts (range 705–810°C), which are also similar to those obtained for amphibole grains from the host granodiorite. Temperatures calculated with the amphibole–plagioclase thermometers are 641 ± 27°C (Ed–Q–Tr–Ab) and 666 ± 32°C (Ed–Ab–Rich–An) for matrix amphibole and plagioclase composition of An21–46 and 742 ± 15°C (Ed–Ab–Rich–An) for amphibole from the clots and plagioclase of An42–49. In the case of amphibole included in plagioclase phenocrysts the pairs have been made only with the plagioclase that hosts the inclusions and there are two possibilities: those that behave like the single crystals of the host granodiorite, with similar temperatures for the two calibrations (762 ± 14 and 756 ± 10°C, respectively), and those that behave like amphibole from the clots (726 ± 11°C; Ed–Ab–Rich–An). Therefore, the obtained amphibole temperatures and pressures, excepting those from the matrix that are lower, are in the range of those from the host granodiorite.

Discussion

Petrogenesis of the Tabaquito batholith

Chemical and mineralogical characterization of the granitoids

Major and trace element compositions along with the mineral assemblages of the Tabaquito granitoids correspond to high-K magmas of I-type affinity formed in a subduction environment. The studied granites are calc-alkalic and magnesian (Fig. 6a and b), mostly plotting in the sub-alkaline field in the TAS diagram (Fig. 6e), and their mafic assemblage is characterized by biotite, hornblende and magnetite, indicating an I-type affinity. These rocks are enriched in incompatible elements and present negative Nb–Ta and positive Pb anomalies, which are distinctive of common subduction-related sources. Relationships of Th/Nb, Y/Nb and La/Nb ratios, which are sensitive to magma sources (e.g. Moreno et al. 2014, 2016), also point to an evident subduction-related source for the Tabaquito granites (Fig. 8), with compositions similar to those of rocks generated in continental area and shoshonitic suites (Fig. 8a). Consistently, biotite composition indicates a calc-alkaline source for these magmas (Fig. 4c), whereas Ti contents versus Mg, Na, K and Al contents of amphibole suggest a subalkaline affinity (supplementary material Fig. 2; Molina et al. 2009).

Chemical and isotopic constraints of the source

These granites have distinctive high K content (see description in the ‘Whole-rock chemistry’ and ‘Chemical and mineralogical characterization of the granitoids’ sections). The origin of high-K calc-alkaline I-type granites is a controversial issue mainly owing to the large range in isotopic compositions, which contributes to the discussion of whether mantle-derived mafic magmas contribute with material or only as a heat source (e.g. Clemens & Stevens 2012; Gao et al. 2016). Recent zircon Hf-isotope data for an equigranular amphibole-bearing granodiorite in the north of the Tabaquito batholith reported by Dahlquist et al. (2018a) (eHf range ~2.0 to +4.5; sample TAB-11) suggest a mainly juvenile (mantle-like) source with some involvement of an older crustal component. This is supported by the slightly negative εNd values of ~1.6, ~1.8 and ~2.4 obtained in this study, and by the available Sr isotope data, which show Sr/Sr, mostly ranging between 0.7039 and 0.7071. Although further data are needed, the current isotopic data point to a mainly juvenile source with the involvement of older crustal material. The Nd model ages calculated here (~1.1 Ga) are similar to the average Hf model age (~1.2 Ga) reported by Dahlquist et al. (2018a), which might suggest partial melting of a late Mesoproterozoic source. However, this age is probably an artefact that results from the mixing of a juvenile crustal or mantle end-member and an older crustal end-member, which is consistent with the isotopic parameters discussed above. In relation to this, Dahlquist et al. (2018a) have suggested the plausible existence of two contrasting, coeval (353 Ma) and not consanguineous parental magmas in the Potrerrillos pluton (located to the NE of the Tabaquito batholith; Fig. 1). One of them has intermediate composition (55–62 wt% SiO2) and a clear juvenile signature (eHf ranging between 2.4 obtained in this study, and by the available Sr isotope data, which show Sr/Sr, mostly ranging between 0.7039 and 0.7071. Although further data are needed, the current isotopic data point to a mainly juvenile source with the involvement of older crustal material. The Nd model ages calculated here (~1.1 Ga) are similar to the average Hf model age (~1.2 Ga) reported by Dahlquist et al. (2018a), which might suggest partial melting of a late Mesoproterozoic source. However, this age is probably an artefact that results from the mixing of a juvenile crustal or mantle end-member and an older crustal end-member, which is consistent with the isotopic parameters discussed above. In relation to this, Dahlquist et al. (2018a) have suggested the plausible existence of two contrasting, coeval (353 Ma) and not consanguineous parental magmas in the Potrerrillos pluton (located to the NE of the Tabaquito batholith; Fig. 1). One of them has intermediate composition (55–62 wt% SiO2) and a clear juvenile signature (eHf ranging between 2.4 obtained in this study, and by the available Sr isotope data, which show Sr/Sr, mostly ranging between 0.7039 and 0.7071. Although further data are needed, the current isotopic data point to a mainly juvenile source with the involvement of older crustal material. The Nd model ages calculated here (~1.1 Ga) are similar to the average Hf model age (~1.2 Ga) reported by Dahlquist et al. (2018a), which might suggest partial melting of a late Mesoproterozoic source.
+0.37 and +12.6), whereas the other is essentially felsic (67–73 wt % SiO$_2$) with a strong crustal signature (εHf of −34.5 to −2.2). Hypothetically, subsequent melting events could give rise to the parental magmas of the Tabaquito batholith (66 wt% SiO$_2$ and variable isotopic parameters) as a result of the variable mixing of two components comparable with these. This hypothesis would also explain the crustal value of the Nb/Ta and (Th/Ta)$_{cr}$ ratios of the studied rocks (Table 2), as it might be inherited from the crustal felsic component.

**Emplacement conditions**

Amphibole-based thermobarometric estimates for the Tabaquito granodiorite and the quartz-diorite enclave yield temperatures that mostly cluster around 750°C and pressures that mainly vary between 1 and 3 kbar (Table 3), with rim compositions and those of amphibole grains from the clots giving a pressure range of c. 1–2.5 kbar. Therefore, amphibole crystallization could have started at pressures around 3 kbar but the emplacement pressure of these magmas should probably be lower than 2.5 kbar, independently of geographical location within the batholith.

Considering that the Tabaquito batholith and the Veladero stock (c. 1.8 kbar and c. 725°C) are representatives of the Carboniferous subduction-related magmatism (Dahlquist et al. 2018a, and references therein), this magmatism represents shallow structural levels (<10 km deep) of the arc.

**Geochronological implications**

**The Tabaquito batholith**

A Carboniferous age of 326–329 Ma for the batholith was first established by Llambías & Sato (1995) based on Rb–Sr whole-rock and mineral data. This age was later corroborated by a U–Pb zircon age of 322 ± 5 Ma obtained by Dahlquist et al. (2018a) (Fig. 9a) on an amphibole-bearing granodiorite from the north of the batholith (sample TAB-11; Fig. 2). To check these ages, we have dated a porphyritic biotite-bearing granodiorite from the south of the batholith (sample TAB-24), which yielded a Carboniferous U–Pb zircon age of 337 ± 2 Ma (Fig. 5a) that is significantly older than the age of the sample from the northern sector. Interestingly, the sample TAB-11 dated by Dahlquist et al. (2018a) presents a group of zircons (n = 6), integrated in the calculated crystallization age (Fig. 9a), with ages ranging between 330 and 347 Ma (Fig. 9; see supplementary file S2 of Dahlquist et al. 2018a). This range of ages overlaps the ages determined for the biotite-bearing granodiorite in the south (TAB-24, concordia age = 337 ± 2 Ma) and correlates the magmatism in both areas (north and south), suggesting that the
crystallization could start around 337 Ma and finish at 322 Ma. Furthermore, the existence of an inherited magmatic zircon age of 336 ± 3 Ma in the early Permian dyke (Fig. 5b) in the north, which is interpreted as magmatic zircon collected from previously crystallized early Carboniferous granites (see next section below), is consistent with this interpretation.

Consequently, zircons from TAB-11 with ages between 330 and 347 Ma may be considered antecrysts; that is, zircon crystals that crystallized from earlier magma pulses and are incorporated in later pulses (e.g. Miller et al. 2007, and references therein). The presence of antecrysts formed at earlier stages and deeper levels that are remobilized and carried to the emplacement level through new magma pulses has been incrementally reported by several researchers (Miller et al. 2007; Barboni et al. 2013; Paterson et al. 2016; Alasino et al. 2017; Dahlquist et al. 2018a, 2019; Siégel et al. 2018; and references therein). Accordingly, Spencer et al. (2016) asserted that a single age should not be assumed as representative of a pluton without a detailed geochronological study, because magmatic systems are often characterized by protracted events.

Despite the apparent difference in age, samples from both the south and the north of the batholith are alike in terms of whole-rock chemistry, mineralogy and P–T conditions as described in previous sections. This might suggest an incremental growth of the batholith via several magma pulses with a probably common source and plumbing system that are apparently emplaced under similar conditions. In the recent literature, incremental growth of plutons and batholiths worldwide involving long periods of time has been reported by several researchers (e.g. Coleman et al. 2004; Glazner et al. 2004; Paterson et al. 2016; Alasino et al. 2017; Hines et al. 2018; Dahlquist et al. 2019), contributing to the extended debate about how magmatic systems are built.

It is important to mention that we have reported 12 U–Pb zircon SHRIMP analyses for TAB-24, whereas Dahlquist et al. (2018a) reported 20 U–Pb zircon LA-MC-ICP-MS analyses for TAB-11. Consequently, we suggest that new zircon analyses are required to verify if TAB-24 has a similar zircon population to that from TAB-11 or not.

The intrusive dykes
Llambias & Sato (1995) attributed the intrusion of north–south dykes described in the ‘Geological setting’ and ‘Whole-rock chemistry’ sections to the extensive Permian magmatism of the Choiyoi group (Permian to early Triassic), although the crystallization age remained unknown.

The first U–Pb zircon ages of 284 ± 4 and 336 ± 3 Ma (Fig. 5b) obtained here for sample TAB-40 (a north–south mafic dyke in the north of the batholith) confirm an early Permian age for this dyke and reveal a significant inheritance of Carboniferous zircons whose age matches the older age found in the Tabaquito granites (Figs 5a and 9). Thus, this evidence indicates that the dykes were developed and intruded into the granite during the early Permian, collecting magmatic zircon previously crystallized in the early Carboniferous granites.

Temporal correlations along the SW margin of Gondwana
U–Pb zircon data of this study together with data from the literature allow us to review the Carboniferous magmatism and correlations along the proto-Pacific margin of Gondwana, which according to Cawood (2005) has constituted an accretionary margin from at least the earliest Ordovician until the present.

In a regional view, the Carboniferous ages of the Tabaquito granitoids (337–322 Ma) are slightly younger than those reported for

![Fig. 11. Reconstruction of the western margin of Gondwana at 340 Ma from Young et al. (2019). Purple lines with triangles on the overriding plate indicate subduction zones, and blue lines denote mid-ocean ridges and transform faults. The numbers indicate regions in which Carboniferous calc-alkaline I-type granitic rocks have been reported. Figure was constructed using GPlates (www.gplates.org).](image-url)
the other calc-alkaline plutons of the Frontal Cordillera and Western Sierras Pampeanas of Argentina (357–342 Ma; Dahlquist et al. 2018a, b), although within error the age of 337 Ma is roughly coeval with those of 342 Ma (Rio Bonette and Veladero stocks; Dahlquist et al. 2018a, b). The correlative I-type calc-alkaline volcanic and plutonic rocks of the Chilean Frontal Cordillera and the Coastal Batholith have ages ranging between 328 ± 3 and 301 ± 2 Ma (Deckart et al. 2014; Maksaev et al. 2014; del Rey et al. 2016) that are in general younger than those of their Argentine counterparts (357–322 Ma) although there are a few overlapping ages (Fig. 10). Although southern granitic outcrops of such Carboniferous magmatism have not been reported in Chile so far (Pankhurst et al. 2006), this magmatism may be correlated with calc-alkaline I-type hornblende granitoids of the eastern North Patagonian Massif with Rb–Sr and U–Pb ages varying between 330 and 320 Ma (Pankhurst et al. 2006). These ages match the crystallization ages of the Tabaquito batholith. Strikingly, I-type calc-alkaline granitoids of the Eastern Cordillera (Perú), which probably formed in a continental arc (Fig. 9; Mišković et al. 2009), yielded similar ages to those of the Chilean arc magmatism (330–301 Ma with inheritance of c. 350 Ma; Chew et al. 2007; Mišković et al. 2009) and match the ages of the Argentine arc magmas. Therefore, based on current geochronological data from the granites of Perú, Chile and Argentina we postulate a palaeo-Pacific continental arc that was active at least between 357 and 301 Ma.

Carboniferous I-type calc-alkaline granitoids have also been reported from various crustal blocks of West Antarctica (Antarctic Peninsula, Thurston Island, Marie Byrd Land, North Victoria Land; e.g. Leat et al. 1993; Pankhurst et al. 1993, 1998; Millar et al. 2002; Korhonen et al. 2010; Yakymchuk et al. 2015; Riley et al. 2017). These granitoids have ages of 358–343 Ma in Marie Byrd Land (Pankhurst et al. 1998; Korhonen et al. 2010; Yakymchuk et al. 2015), c. 347 Ma in North Victoria Land (Henjes-Kunst & Kreuzer 2003) and c. 349 Ma in Thurston Island (Riley et al. 2017). These ages are comparable with those of the arc magmatism of Argentina (357–322 Ma; Fig. 10) but slightly older than those reported for the Chilean calc-alkaline granitoids (328–301 Ma; Fig. 10). These ages also find correlatives in the 351–342 Ma I-type granitoids of the Tobin suite of western New Zealand (Tulloch et al. 2009). It is also noteworthy that scarce SHRIMP U–Pb zircon data from the Antarctic Peninsula reveal a c. 330 Ma thermal event (Millar et al. 2002) that coincides with the ages of the South American magmatism discussed here.

Fig. 12. Schematic geodynamic model showing the possible fluctuation of the subduction angle of the oceanic plate. Red indicates Carboniferous magmas; pink indicates Permian magmas.
The Carboniferous Tabaquito batholith

Tulloch et al. (2009) indicated that I-type granites of c. 350–340 Ma age (Tobin Suite in New Zealand) constitute the only magmatic event that can be recognized throughout the entire Gondwana margin from fold belts of eastern Australia to New Zealand, Marie Byrd Land and possibly North Victoria Land. Consequently, this magmatic event can now be extended to the Thurston Island (West Antarctica) and South America as described above. Therefore, the age correlation between South America, Antarctica and New Zealand suggests that these regions could have been contiguous in the Carboniferous (Fig. 11), forming an accretionary margin, although with distinctive features in the subduction process (i.e. normal subduction, flat subduction, etc.).

Geodynamic model for 27–34°S latitude

Considering that Carboniferous calc-alkaline rocks from Chile and Argentina at this latitude formed part of the same continental arc, here we compare their chemical and isotopic data to assess the characteristics of the geodynamic setting and their relation with the generation and evolution of the arc magmatism at this latitude.

The Argentine Carboniferous granites are richer in K₂O than their Chilean equivalents (Fig. 7d), which translates into higher alkali contents plotting in the alkaline field of the TAS diagram and higher MALI values (Fig. 7b and c). This potassium enrichment is consistent with a continental arc in which the Carboniferous granitoids of Argentina would be located further away from the trench than their Chilean counterparts (Fig. 12a) (see discussion by Chapman et al. 2017). In such a scenario the increase in K₂O would result either from increasing depth of melting (Marsh & Carmichael 1974) or from a greater involvement of the older continental crust (Hildreth & Moorbath 1988). The isotopic data indicate that a greater participation of the older continental crust does not seem to be the cause of the K₂O enrichment observed in the Argentine granitoids. Thus, published Hf- and O-isotope zircon data (εHf = −34.5 to +14.1 and δ¹⁸O = 6.1–7.3‰; Deckert et al. 2014; Dahlquist et al. 2018a) and Nd and Sr whole-rock isotope data (εNd = −1.7 to −4.2 and Sr/Srᵢ = 0.7057–0.7098; Parada et al. 1981, 1999; Nasi et al. 1985), along with those obtained here, suggest variable involvement of mantle and crustal components in their sources, albeit with a probably greater imprint of the juvenile end-member in the Carboniferous Argentine granitoids (εHf ranging between −34.5 and +14.1 with predominance of positive values; Dahlquist et al. 2018a).

As revealed in the ‘Geological implications’ section, the Argentine granitoids at this latitude are older (357–322 Ma) than the Chilean correlates (328–307 Ma) with a few overlapping ages (Fig. 10). Migration of the magmatism to the west could have been caused by steepening of the subducting plate during slab roll-back (Fig. 12a and b). Such a geodynamic scenario fits well within the geodynamic switching model that explains the coeval production of Carboniferous I-type arc and A-type retro-arc granitoids (Alasino et al. 2012; Dahlquist et al. 2018a).

As described in the ‘Field relations of the Tabaquito batholith’ section, abundant dykes were emplaced in the Tabaquito batholith. These dykes are part of the extensive Permian–Triassic magmatism of the Frontal Cordillera called the Choyoi group (see Llambías & Sato 1995; Rocher et al. 2015; Sato et al. 2015; del Rey et al. 2016). Geochronological and geochemical data suggest that these dykes can represent a subduction-related magmatism at 284 ± 4 Ma. The geochronological data reported here for the dykes and the Carboniferous granitoids strongly suggest that the Carboniferous magmatic arc was overprinted by the early Permian magmatic arc (Fig. 12c).

Summarizing, we propose that the early Carboniferous and Permian magmatism results from a continuous subduction-related magmatic evolution, which continued until the present. The sequence of events agrees with the idealized tectonic evolution of an Andean orogenic cycle in which variation over time of the angle of subduction is the key factor controlling magmatic processes (Fig. 12), as was postulated by several researchers (Alasino et al. 2012; Rocher et al. 2015; del Rey et al. 2016; Dahlquist et al. 2018a). Recently, del Rey et al. (2016) have postulated that the Andean subduction was a continuous process since the Middle Permain–Triassic (normally established since the Mesozoic).

We conclude that the Andean magmatic cycle at this latitude might be extended to Carboniferous time, where the arc environment was mostly continuous from the early Carboniferous to the present, but marked by compositional changes in space and time in response to changes in the subduction angle of the oceanic plate.

Conclusions

The new Carboniferous SHRIMP U–Pb zircon age of 337 Ma obtained here along with previously published U–Pb data suggest that the Tabaquito batholith represents a long-lived magmatic plumbing system formed through at least two magmatic pulses, one at 337 Ma and the other at 322 Ma, emplaced at shallow conditions (c. 750°C and 2 kbar). Furthermore, crystallization and inherited ages (284 ± 4 and 336 ± 3 Ma) of the studied mafic dyke suggest the superimposition of Permian magmatism over the Carboniferous magmatism in this area.

Major and trace element compositions of the granodiorite, mafic enclave and sampled dykes are consistent with a subduction setting (continental arc). Chemical and mineralogical similarities of the studied rocks from the south and the north suggest the existence of a long-lived (c. 15 myr) magmatic plumbing system, with the intrusion of younger batches into older crustal mashes.

The isotope composition of these rocks (εHf range −2.0 to +4.5; εNd range −1.6 to −2.4; Sr/Srᵢ 0.7039–0.7071) might result from mixing of a mafic to intermediate end-member with a juvenile signature and a felsic end-member with a crustal signature (probably an older continental crust).

Comparison between Carboniferous arc-related granites of Chile and Argentina indicates that the Argentine granites are enriched in K₂O. However, this K₂O enrichment does not seem to be related to a major involvement of the continental crust as suggested by isotope compositions.

Difference in age between the Argentine Carboniferous arc granitoids and their Chilean counterparts points to a migration of the magmatism towards the trench as a consequence of a change of the subduction angle. Accordingly, the Andean magmatic cycle can be extended to Carboniferous time, where the arc setting would be continuous to the present and the compositional magma changes in space and time would be controlled by fluctuations of the subducting plate.

The widely recognized Carboniferous (c. 350–340 Ma) magmatic event might suggest that South America, West Antarctica and New Zealand were part of the same subduction margin in an accretionary orogen developed in SW Gondwana.

Acknowledgements We dedicate this work to the memory of our beloved friend and colleague Professor Dr Carmen Galindo. We are grateful to the staff of the Parque Nacional San Guillermo (San Juan Province, Argentina) for giving us the permissions to carry out the geological work in the park. R. Stern is acknowledged for his valuable comments on an earlier version of the paper. We thank an anonymous reviewer and R. A. VanderLeest for the thorough revision of the paper and for their insightful comments that have greatly improved the quality of the paper. We are also very grateful to T. Rooney for his efficient and helpful editorial handling as well as for his detailed comments and suggestions.

Funding Financial support for this paper was provided by Argentine public grants FonCyT PICT 2016 0843, PIP0178 CONICET, Spain public grant CGL2016-76439-P, and a stay developed by I.A.D. in the Geosciences Institute of the São Paulo University supported by grant FAPESP 2018/06837-3.
Author contributions JAM: Investigation (equal), Visualization (equal), Writing - Original Draft (lead), Writing – Review and Editing (lead); JAD: Investigation (equal), Project Administration (lead), Resources (lead), Supervision (equal), Writing – Original Draft (supporting); MMMC: Investigation (equal), Visualization (equal), Writing – Original Draft (supporting); PHA: Investigation (equal), Writing – Original Draft (supporting); MAL: Investigation (equal), Writing – Original Draft (supporting); MAB: Formal Analysis (supporting), Investigation (equal); CG: Formal Analysis (supporting), Investigation (equal), Resources (equal); PSZ: Investigation (equal), SR: Investigation (equal)

Scientific editing by Tyrone Rooney

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