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Artículos de Investigación

The country rocks of Devonian magmatism in the North Patagonian Massif and Chaitenia

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Abstract:

Previous work has shown that Devonian magmatism in the southern Andes occurred in two contemporaneous belts: one emplaced in the continental crust of the North Patagonian Massif and the other in an oceanic island arc terrane to the west, Chaitenia, which was later accreted to Patagonia. The country rocks of the plutonic rocks consist of metasedimentary complexes which crop out sporadically in the Andes on both sides of the Argentina-Chile border, and additionally of pillow metabasalts for Chaitenia. Detrital zircon SHRIMP U-Pb age determinations in 13 samples of these rocks indicate maximum possible depositional ages from ca. 370 to 900 Ma, and the case is argued for mostly Devonian sedimentation as for the fossiliferous Buill slates. Ordovician, Cambrian-late Neoproterozoic and "Grenville-age" provenance is seen throughout, except for the most westerly outcrops where Devonian detrital zircons predominate. Besides a difference in the Precambrian zircon grains, 76% versus 25% respectively, there is no systematic variation in provenance from the Patagonian foreland to Chaitenia, so that the island arc terrane must have been proximal to the continent: its deeper crust is not exposed but several outcrops of ultramafic rocks are known. Zircons with devonian metamorphic rims in rocks from the North Patagonian Massif have no counterpart in the low metamorphic grade Chilean rocks. These Paleozoic metasedimentary rocks were also intruded by Pennsylvanian and Jurassic granitoids.

Keywords: Devonian, Metamorphic complexes, U-Pb zircon ages, North Patagonian Massif, Chaitenia.

1. Introduction

The Paleozoic evolution of the western margin of Gondwana in its South American segment is thought to have involved successive collision of microcontinental terranes and associated orogenies that developed along the margin (Fig. 1). However, the lithological constitution and extent of these terranes, in particular Chilenia, has been difficult to assess due to poor exposure and, locally, the lack of precise dating of the rocks.

Álvarez et al. (2009, 2011, 2013a,b) studied metamorphic complexes in areas close to Gneisses de la Pampa outcrops, in the Huasco Valley of northern Chile, which were initially considered to represent the crust of Chilenia (Ramos et al., 1984), but were later shown to be a metamorphosed Carboniferous pluton (Álvarez et al., 2009; Hervé et al., 2014). Álvarez et al. (2011) found a population of 580 to 530 Ma detrital zircon ages which they consider to have been derived from the erosion of a magmatic/metamorphic source that possibly forms a significant component of the Chilenia microcontinent. Zircon U-Pb data obtained in the Quebrada Seca Schists, a metamorphic unit which crops out near the Pampa gneisses, yielded an age of 486±6.5 Ma (Álvarez et al., 2013a) and allowed the conclusion that the plutonic protolith of this unit was emplaced in the Chilenia terrane close to the time of the Cambrian-Ordovician boundary, i.e., before the Devonian collision. According to the same authors, the Quebrada Seca Schists are the only known exposed rocks of the Chilenia basement in Chile. However, the assumption that the Quebrada Seca schists have an igneous protolith is not documented, and the analytical data were not presented.

In the present-day North Patagonian Andes, recent SHRIMP U-Pb dating of the crystallization age of zircon from intrusive igneous bodies, together with their O and Lu-Hf isotopic characteristics (Hervé et al., 2016), suggested that Devonian igneous rocks constituted two magmatic belts: an eastern one emplaced in the continental crust of Patagonia and the other developed in an oceanic island arc to the west that was later accreted to Gondwana. The oceanic island arc terrane has been referred to as Chaitenia (Hervé et al., 2016) and is thought to have extended southwards from the Huincul lineament, the southern limit of Chilenia (Ramos et al., 1984). Chernicoff et al. (2013) have proposed that a Devonian magmatic arc was developed over the western edge of a "Southern Patagonia terrane", during east-directed subduction previous to collision with Patagonia, but they considered that the arc was built over an old continental fragment.

As a step towards characterising the nature of the crust into which the two magmatic belts were emplaced, we present SHRIMP U-Pb zircon ages on detrital zircons from thirteen samples of metamorphic rocks from the surrounding areas of known Devonian intrusive bodies, as well as four further crystallization ages of plutons which intrude them. Localities sampled in Chile are indicated in the 1:1.000.000 Geological Map of Chile (SERNAGEOMIN, 2003) as Devonian-Carboniferous or Paleozoic-Triassic based on lithological correlation with mapped and dated units. Those in Argentina belong to the widespread Colohuincul Complex and Cushamen Formation.

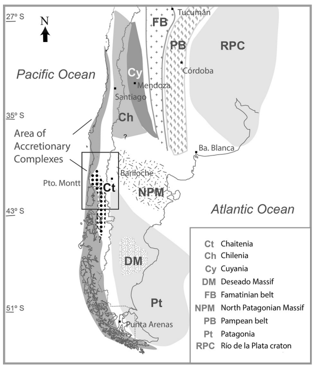

Fig. 1.

Fig. 1. General location map of the studied area in the north Patagonian Andes and Massif.

2. Geological setting

Devonian plutonic rocks are known from various localities in the studied region (Fig. 2), among which some now have well-established U-Pb ages close to 400 Ma (Pankhurst et al., 2006; Godoy et al., 2008; Hervé et al., 2013); these include tonalites and granites around San Martín de los Andes and porphyritic granite at Colán Conhue, southeast of Esquel. Further Devonian intrusive rocks are now known along the western slope of the Andes at Pichicolo, Chaitén and Yelcho lake (Hervé et al., 2016).

The Pre-Jurassic basement of Patagonia contains sedimentary or metasedimentary rocks that generally lack preserved fossils and have long been considered to be Paleozoic or Proterozoic. In the studied area on the Chilean side of the Andes such rocks are comparable to those in the extensive Eastern Andes Metamorphic complex (Hervé, 1988; Hervé et al., 2007) where previous U-Pb dating of detrital zircon has suggested Devonian to Late Triassic depositional ages (Hervé et al., 2003). Low-grade slates at Buill (Fig. 2) are uniquely associated with trilobite fossils (Levi et al., 1966; Fortey et al., 1992), albeit so far only found in boulders lithologically similar to rocks cropping nearby. They are taken as marking a reliable Devonian age for deposition of the slate protolith. The relationship to turbidite successions and pillow basalts and associated ultramafic rocks in the vicinity (Crignola, 1999; Hervé et al., 2017) has not been established clearly, as outcrops in this area are sparse and with difficult access due to dense forests. Metamorphic rocks in the Coastal Range are assigned to a paleo-accretionary complex which is represented as of Paleozoic-Triassic age on the 1:1.000.000 Geological Map of Chile. The eastward extension of the accretionary complex is not well established.

On the Argentine side of the Andes, similar low-grade metasedimentary rocks are represented by the Colohuincul Complex in the cordilleran zone around Bariloche (Fig. 2) (Dalla Salda et al., 1991) and the Cushamen Formation farther east (Varela et al., 2005). A Devonian age for the latter seems reasonable on the basis of Rb-Sr whole-rock data (Ostera et al., 2001) and U-Pb zircon data for a sample thought to be part of the formation from south of El Maitén that shows Silurian provenance and significant Devonian metamorphism (Pankhurst et al., 2006).

In the Colohuincul Formation, García-Sansegundo et al. (2009) presented evidence for early high-pressure deformation and metamorphism followed by intermediate-low grade conditions during decompression. Electron microprobe Th-U-Pb dating of monazite from high-pressure migmatites (Cruz Martínez et al., 2012) yielded ages of 392±4 and 350±6 Ma, which were assigned to these events; they ascribed the metamorphism to Devonian collision of Chilenia with Patagonia, implying southward extension of the Chilenia terrane to the present 41° S latitude. Other previous maximum possible depositional ages in the Colohuincul Complex are the ca. 1000 Ma (Ramos et al., 2010) at Cuesta de Rahue, 420 Ma in a schist enclave in the 401 Ma San Martín tonalite, and ca. 380 Ma in a paragneiss in the main range near Liquiñe (Hervé et al., 2016).

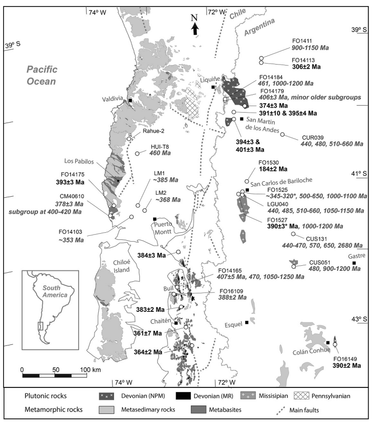

Fig. 2

Fig. 2. SHRIMP zircon ages in the studied area. Grey numbers indicate main age peaks of detrital zircons in metasedimentary rocks; * indicates metamorphic ages; numbers in bold type are igneous rock crystallization age. Data from this paper and Hervé et al. (2016).

3. Methodology

Samples were collected from localities displaying the typical outcrop characteristics of the different units, as detailed below. Petrographical observations in thin sections and X-ray diffraction (XRD) studies were carried out at the Laboratory for the Analysis of Solids (LAS) at Universidad András Bello, Santiago. For samples numbered with the prefix FO, zircon was separated by standard methods of crushing, grinding, Wilfley table, magnetic and heavy liquids at Universidad de Chile, Santiago. Zircon separation for earlier samples from Argentina was carried out in a similar way at British Geological Survey, UK.

Isotopic analyses were undertaken at the Research School of Earth Sciences, The Australian National University, Canberra. Zircon grains were mounted in epoxy and polished to about half-way through. Cathodo-luminescence (CL) images were obtained for all grains to select appropriate areas for analysis. U-Th-Pb analyses were carried out using sensitive high-resolution ion microprobes (SHRIMP II and SHRIMP RG) following procedures similar to those described by Williams (1998 and references therein). From each sample, 15 to 20 grains were analysed when an igneous crystallization age was required, and 60 or more grains if possible when identification of sedimentary provenance was the objective. Crystallization ages, where calculated, are reported here with 95% confidence limits. The International Chronostratigraphic Chart time-scale of Cohen et al. (2013) is used throughout.

TABLE 1. SUMMARY OF ZIRCON AGES AND PROVENANCE FOR DEVONIAN SAMPLES FROM PATAGONIA.

Sample No.	Locality	Lithology	Lat. S	Long. W	MPSA* (Ma)	Provenance (Ma)
Metasedimentary Rocks						
Eastern Andes						
FO14111	Cuesta de Rahue	Schist	39°23’41.6”	70°48’52.9”	<900 Ma, possibly <480	Main provenance 1050, 1250, 1380
FO14184	Estero El Loco	Meta-sandstone	39°58’02.0”	71°41’34.4”	Post-460	Dominant *ca.* 1090 and older
FO14179	Río Lipinza	Schist enclave	39°59’46.9”	71°42’18.2”	406±3 (19)	480, 580-680, 1090, 1350, 2600
CUR039	Río Collon Cura	Schist	40°22’07.5”	70°39’46.6”	*ca.* 440?	(330-370), 440, 480, 510-660, 800-1250, 2000, 2650, 3500
FO1525	SE lago Gutiérrez	Mica schist	41°14’51.9”	71°26’47.4”	*ca.* 500	500-650, 1000-1100, 1850, 3300? Metamorphism 260-330
LGU040	SE lago Gutiérrez	Biotite gneiss	41°14’49.2”	71°26’52.0”	*ca.* 440?	*ca.* (370), 440, 485, 510-660, 1050-1150, 1410, 1830, 3200
FO1527	Brazo Tronador	Granitic gneiss	41°17’52.2”	71°35’48.8”	*ca.* 470?	480, 1100-1200 and older cores. Metamorphism 390 (375?)
CUS131	Cordón de Angostura	Micaschist	41°45’27.9”	70°29’49.3”	*ca.* 440?	440-470, 570, 650-740, 1050-1150, 1350, 1900, 2680
CUS051	Cushamen	Micaschist	42°11’35.0”	70°29’31.0”	*ca.* 480?	390, 480, 790, 900-1200, 1500, (2450)
Western Andes						
Hui-T8	ENAP drill core	Mica-garnet schist	40°35’35.4”	73°14’38.0”	400 Ma?	(240-370), 460, 580-640, 1080, 1200, 2600-2,660
LM2†	Los Muermos drill core	White mica schist	41°21’25.6”	73°16’28.7”	370?	387, 465, 570, 650, 1070, 1240, *ca.* 1900
LM1†	Los Muermos drill core	White mica schist	41°23’52.6”	73°02’50.3	355?	385, 411, 470, 500-640, *ca.* 1080
FO14103†	Los Muermos	Metasandstone	41°27’38.4”	73°44’22.5”	365?	380, 540
CM40610	Lacui	Mylonite	41°32’03.7”	73°47’38.7”	378±3 Ma (21)	range extends to 410, 470, (1040), *ca.* 2650
FO14165	Buill	Siltstone	42°25’12.6”	72°42’07.0”	407±5 Ma (5)	470, *ca.* 550-650, 1050-1250, *ca.* 1400 and Archaean
FO16109	Lago Reñihue	Siltstone	42°30’07.7”	72°47’18.5”	388±2 Ma (37)	(300-330), older individual ages

* **MPSA:** Maximum possible sedimentary age.

† from Hervé *et al*. (2016).

Sample No.	Locality	Lithology	Lat. S	Long. W	Intrusive Age (Ma)	Provenance (Ma)
Igneous Rocks						
FO14113	Cuesta de Rahue	Granodiorite dyke	39°23’59.0”	70°49’00.7”	306±2 (12)*	Minor inheritance 1000-1200
FO1530	N of lago Nahuel Huapi	Tonalite	41°01’36.8”	71°19’32.2”	184±2 (16)*	n.d.
FO14175	Zarao	Rhyolite	41°18’49.9”	73°38’23.0”	382±3 (7) or 393±3 (13)*	n.d.
FO16149	Colán Conhue	Granite	43°17’57.1”	69°35’45.2”	390±2 (22)*	n.d.

Table 1

4. Results

The results obtained are summarized in table 1 and discussed below. U-Pb isotope plots and detrital zircon age distributions are shown in figures 3-5 and data for the igneous samples in figure 6.

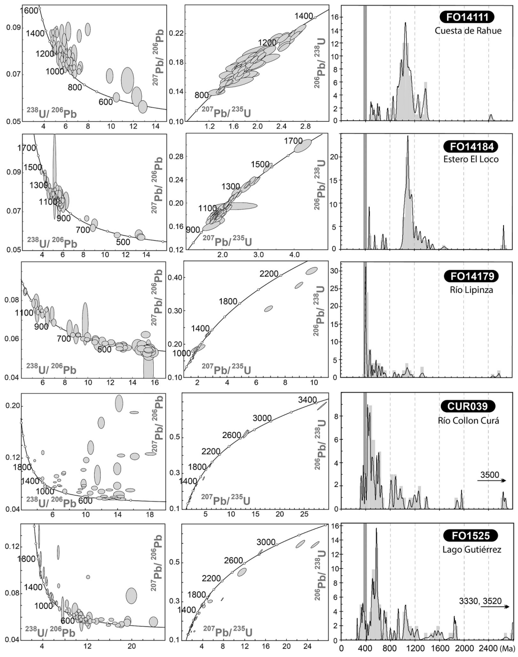

Fig. 3

Fig. 3. Tera-Wasserburg (data uncorrected for common Pb), Wetherill (204Pb-corrected) and preferred age versus frequency/relative probability diagrams for metasedimentary rock sample zircon from the eastern (continental) Devonian belt (continued in figure 4)

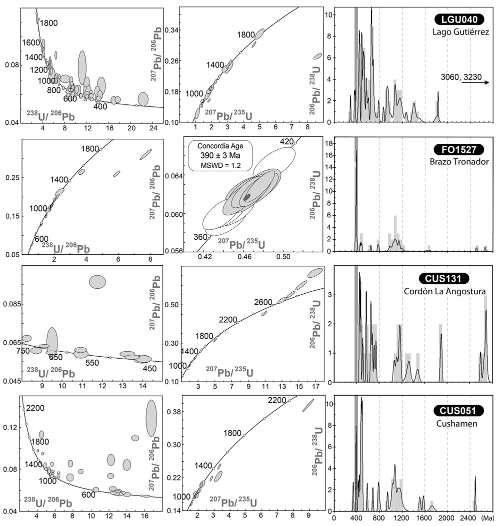

Fig. 4.

Fig. 4. Continuation of figure 3. The age for FO1527 is a Concordia Age (sensu Ludwig, 2003) for metamorphic zircon rims, ignoring the data plotted as white ellipses; uncertainty level is 2s.

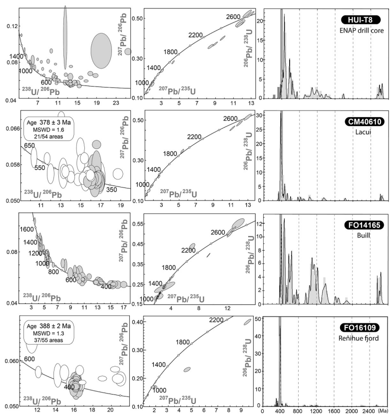

Fig. 5

Fig. 5. Tera-Wasserburg (data uncorrected for common Pb), Wetherill (204Pb-corrected) and preferred age versus frequency/relative probability diagrams for metasedimentary rock sample zircon from the western Devonian belt (island arc). The ages for significant clusters shown for CM40610 and FO16109 are weighted mean 206Pb/238U ages after correction for common Pb using the 207Pb measurements; uncertainties are 2s.

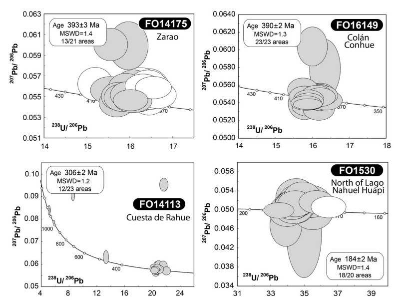

Fig. 6

Fig. 6. Tera-Wasserburg diagrams for igneous rock zircons dated in this study. The calculated ages are weighted mean 206Pb/238U ages after correction for common Pb using the 207Pb measurements, ignoring data plotted as white ellipses; uncertainties are 2s.

4.1. Metasedimentary rocks

FO14111 is a massive white mica schist, collected from the highest outcrop at Cuesta de Rahue, North Patagonian Massif, in Argentina. It has planar Sp N75W/44N and planar cross-cutting quartz-chlorite veins up to 50 cm wide. U-Pb ages of zircons (Fig. 3) indicate a broad spectrum in the relative probability diagram, predominantly in the range 930-1380 Ma with a main peak at ca. 1050 Ma, but also with eight 206Pb/238U ages in the range 485-845 Ma (three of these close to 500 Ma). Due to their scattered nature it is not possible to confidently assign an age to the youngest provenance, but the depositional age is certainly younger than 900 Ma, possibly younger than 480 Ma. Schist from a nearby locality analysed by Ramos et al. (2010) gave a ca. 1,000 Ma age for the youngest detrital zircons; according to these authors the schists here belong to the Colohuincul Complex and were thrust towards the west.

FO14179 from Río Lipinza is a hornfels, probably indicating a sandstone protolith, which was sampled as an enclave in a dioritic intrusive rock emplaced in mica schist together with a suite of aphanitic to microphaneritic dykes. The obtained zircon age distribution (Fig. 3) shows a youngest concentration of ca. 400 Ma; 19 of these give a weighted mean of 406±3 Ma which is taken as pertaining to an Early Devonian igneous intrusion in the provenance area. The detrital pattern also shows minor Ordovician, Neoproterozoic, Mesoproterozoic and Archaean peaks. In the Geological Map of Chile (SERNAGEOMIN, 2003) the location of this sample, as well as the one that follows (FO14184), is labelled as Liquiñe Metamorphic Complex, of Paleozoic to Triassic age.

FO14184 is a schist boulder from estero El Loco, lithologically similar to coarse-grained schists that crop out in this small stream with a limited catchment area. It is a quartzose banded metasandstone containing biotite, white mica and garnet, with a sub-vertical NW main foliation. The local schists contain andalusite and cordierite porphyroblasts, indicating medium-grade low P/T metamorphism, probably related to igneous intrusions known to occur in the area (see below). The detrital zircon ages (Fig. 3) indicate a dominant "Grenville" peak at 1090 Ma, tailing off to ca. 1450 Ma. There a few apparent late Neoproterozoic ages but the youngest three seem to define Late Ordovician provenance, limiting deposition to post-460 Ma. Regional proximity and age pattern similarity with FO14179 suggest a similar depositional age for both samples.

CUR039 is a schist from Collon Curá, southwestern Río Negro Province. The outcrop, located at route RN234, 8 km north of junction with RN237, is injected by leucocratic veins and mafic dykes, but the sample is from a vein-free area. The major inheritance ranges in age from 400 to 660 Ma, with peaks at 440-470, 510 and 580-610 Ma (Fig. 3) Four younger grains (320-365 Ma) have high common Pb and may have been affected by the later intrusions. The depositional age is post-Ordovician, possibly Devonian. There is minor older provenance at 800-1400 Ma as well as traces at ca. 1900 and 2650 Ma and a single concordant grain at 3500 Ma.

FO1525 is a mica schist from the southeastern end of lago Gutiérrez. The U-Pb zircon age distribution (Fig. 3) shows prominent but dispersed clusters between 500 and 650 Ma, rather minor "Grenville-age" peaks (1050 Ma) and ca. 1850 Ma, as well as some Archaean ages back to ca. 3500 Ma. At the younger end of the spectrum scattered Late Paleozoic ages include four clear metamorphic rims with Permo-Carboniferous ages of 260-330 Ma. This sample shows little evidence of either Ordovician or Devonian provenance, nor of Early Devonian metamorphism. This and the two following samples form part of the Colohuincul Complex (Cruz Martínez et al., 2012).

LGU040 is a sample of biotite gneiss taken from very close to the locality of FO1525. The zircon age spectrum (Fig. 4) shows a single grain at 284 Ma and two at ca. 360 Ma, the reality of which is confused by rather high common Pb, but a peak at 400 Ma followed by the main one at 485 Ma. The older part of the distribution spectrum is very similar to that of FO1525, with significant peaks at 520, 570 and 660 Ma and the same spread of Mesoproterozoic, Paleoproterozoic and Archaean ages.

FO1527 is a granitic gneiss from lago Mascardi (Brazo Tronador) shows Devonian ages (370-400 Ma) for zircon areas with extremely low Th/U ratios, which are interpreted as metamorphic rims (Fig. 4). Of these, the four youngest yield a weighted mean age of 376±5 Ma, whereas 11 others yield 390±3 Ma. The latter result confirms the Devonian age of the main metamorphism obtained by Cruz Martínez et al. (2012); the former may reflect slight Pb-loss, but is still older than the 350±6 Ma assigned by Cruz Martínez et al. (2012) to low-grade post-metamorphic decompression. Our data for zircon cores with normal igneous Th/U ratios show a range of Ordovician, "Grenvillian" and older ages similar to the above samples. CL images show some of the ca. 1000 Ma areas to be overgrowths, suggesting a "late-Grenvillian" metamorphism.

CUS131 is a Cushamen Formation schist sample from río Chico (Cordón de la Angostura) in Río Negro province, 32 km east of Ñorquinco. The youngest zircon ages obtained are 440-460 Ma (Fig. 4). Other significant groups are Late Neoproterozoic (570, 650 Ma), Mesoproterozoic (1000-1200 and 1,400 Ma), ca. 1900 Ma and 2600-2700 Ma.

CUS051 is another mica schist sample from the Cushamen Formation, 14 km east of Cushamen village. The main provenance is Early Ordovician, the main peak in the distribution being at 480 Ma (Fig. 4). Younger ages are mostly associated with high common Pb but there is one good analysis at 385 Ma. There is a significant Mesoproterozoic group at 1000-1200 Ma with a peak at 1070 Ma.

FO14165 is a 10 cm thick low-grade fine-grained metasandstone interbedded with dark grey slates near the town of Buill. This unit, as well as that of the following sample, belongs to the Paleozoic-Triassic unit in the Geological Map of Chile (SERNAGEOMIN, 2003). U-Pb data were originally reported by Hervé et al. (2017) but are repeated here as a control for comparison (Fig. 5). The zircon age versus probability diagram shows wide dispersion, with some poorly-defined age peaks corresponding to Devonian, Ordovician, 550-650 Ma, early "Grenville" (1100-1250 Ma), ca. 1400 Ma and even Archaean. This is the only sample with a constrained stratigraphic age independent of the U-Pb zircon dating: the depositional age of this unit is well established by its trilobite content, which led Fortey et al. (1992) to consider the fossil fauna as of Malvinokaffric affinities and indicating Lower to early Middle Devonian (Emsian-Eifelian) deposition. Five of the youngest grains give a good weighted mean 206Pb/238U age of 407±5 Ma, which is consistent with this depositional age.

FO16109 from the southwest shore of Reñihue fjord is a fine-grained metasandstone (Fig. 7A, B) interbedded with pillow metabasalts (Fig. 7B, C). The three youngest 206Pb/238U ages obtained are c. 303 Ma, and another is ca. 330 Ma, but almost all the remainder fall in the range 375-400 Ma, from which 37 give a weighted mean of 388±2 Ma, with an acceptable MSWD of 1.3 (Fig. 5). The younger ages are all associated with rather high common Pb contents and may not be reliable. Thus the most robust estimate for a maximum depositional age is Middle Devonian, and the sediment protolith could well be part of the Devonian basement, as well as the enclosing pillow metabasalts.

HUI-T8 is a mica schist from the bottom of ENAP borehole HUILMA-1 west of Osorno. The youngest five zircons dated (Fig. 5) are spaced out in the range 235-370 Ma and all have high common Pb so that little confidence can be placed in them as real detrital ages. A major concentration in the range 400-500 Ma with a notable peak in the distribution at 460 Ma implies that deposition of the protolith was no older than Ordovician and probably Devonian. This is in accordance with the supposed Devonian age assigned to the Llanquihue metamorphic complex in this area by McDonough et al. (1997, and written personal communication 2001) and Hervé et al. (2016). There are minor older detrital components of 580-640 Ma, 900-1400 Ma and ca. 2650 Ma.

CM40610 is a metasandstone from the Lacui unit of the Bahia Mansa Metamorphic Complex of the Chilean Coast Range. The U-Pb analyses (Fig. 5) show a broad range of Devonian ages (370-410 Ma), the younger set of 21 yielding a possible provenance age of 378± 3 Ma. There is a small resolvable sub-group at 470 Ma and scattered older ages include three Archaean grains at 2700 Ma but very few "Grenville" ages.

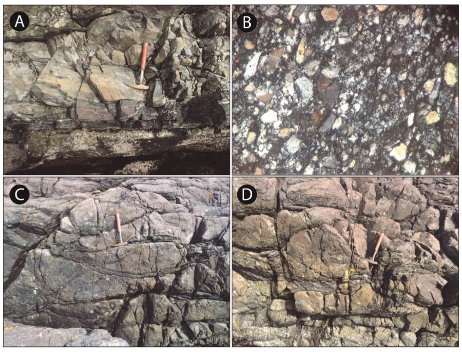

Fig. 7

Fig. 7. A. Metasandstone layer intercalated between the pillow metabasalts at Reñihue fjord from where sample FO16109 was collected, which has Devonian detrital zircons; B. FO16109 metasandstone under the microscope, showing faintly oriented quartz and feldspar angular to subrounded grains in a recrystallized quartzose matrix. Crossed polars, frame is ca. 4 mm wide; C. Metabasalt at Reñihue fjord showing well preserved pillow structures; D. Pillowed metabasalt at Reñihue fjord interpreted as tectonically inverted.

4.2. Igneous Rocks

FO14113 is a granodiorite dyke, several metres wide with biotite-rich inclusions, which intrudes the Cuesta de Rahue schists, but has no penetrative foliation. Other white-mica bearing pegmatitic dykes are associated with the one dated here. Some of the dated zircon grains (Fig. 6) are Mesoproterozoic (1000-1200 Ma) and one is Archaean (these could easily have been assimilated from the country rock schist), but the majority (twelve) yielded a weighted mean Pennsylvanian age of 306±2 Ma, which is interpreted as the crystallization age of the granodiorite. Four younger ages probably reflect degrees of Pb-loss. Dyke emplacement is thus contemporaneous with that of the Coastal Batholith in south-central Chile (Fig. 1).

FO1530 is a tonalite from the northern shore of lago Nahuel Huapi. It probably intrudes the Colohuincul Formation known to crop out in this area (Cruz Martínez et al., 2012) and was considered as possibly Paleozoic. However, our results show a simple spread of Jurassic 206Pb/238U ages from 174 to 190 Ma (and a single 970 Ma), with a clear main peak at 184±2 Ma (Fig. 6).

FO14175 is a rhyolite which forms part of the accretionary complex of the Chilean coastal basement at Zarao. U-Pb zircon data (Fig. 6) yield 206Pb/238U ages that range from 376 to 412 Ma, beyond expected analytical error. Discounting one with excessive common Pb, the youngest seven give a weighted mean of 382±3 Ma (MSWD=0.7) and the next thirteen give 393±3 Ma (MSWD=1.4). Intrusion must have occurred during the Eifelian (or possibly Emsian) age, in accordance with previous dating of this body as 397±1 Ma by Duhart et al. (2001) and Hervé et al. (2016). The contacts with surrounding metamorphic rocks are necessarily tectonic, as the country rocks have younger detrital zircons (Hervé et al., 2016).

FO16149 is a sample of the Colán Conhue porphyritic granite, previously dated as 394±4 Ma by Pankhurst et al. (2006). This was taken for confirmation of the Devonian age and to see if there might be an inheritance record. The U-Pb age given by 22 of the 23 analyses (excluding the lowest age of 382 Ma) is 390±2 Ma, with an MSWD of 1.1 (Fig. 6). This is satisfactorily well within error of the previous result, but the data reveal no useful evidence of older inheritance.

5. Discussion

5.1. Pre-Devonian detrital zircon provenance analysis

In both the present-day Andean fore-arc and the North Patagonian Massif, detrital zircon age distributions in the sampled metamorphic rocks show variable pre-Devonian provenance but are generally consistent with derivation from the contemporaneous continental margin of Gondwana.

An Archaean component is found in most samples and is volumetrically significant at Buill and Río Chico; even a few grains of Paleoarchaean (ca. 3,500 Ma) are characteristic of the outcrops at lago Gutiérrez and río Collon Curá. This component does not seem to occur in the more westerly outcrops. The sources of the Archaean detritus are uncertain, especially in view of low abundance consistent with multi-cycle reworking, but would be compatible with an ultimate source in southern Africa, the only nearby area within the Gondwana assemblage that has rocks proven to extend back in time to 3500 Ma (Drabon et al., 2017). Similar low-abundance Archaean provenance is occasionally found in rocks of many ages in southern South America (Pankhurst et al., 2006; Hervé et al., 2013).

In the northeast of the study area (cuesta de Rahue and estero El Loco) a spread of “Grenville-age” zircons predominate in the detrital material of the Colohuincul Formation, as previously noted by Ramos et al. (2010). The range extends to ca. 1400 Ma, a spread of Mesoproterozoic ages that is typically found in the basement of the Western Sierras Pampeanas of NW Argentina exposed by Tertiary uplift (see Rapela et al., 2016 for review); the comparison even extends to similar traces of Archaean provenance. The proto-Gondwana margin of continental South America would thus seem to be a probable source area. Deposition could conceivably have been as early as early Neoproterozoic although traces of Ordovician zircon suggest that mid-Paleozoic is more likely, as noted below. It is significant that the same spread of Mesoproterozoic zircon ages (ca. 1100, 1250 and 1350-1400 Ma) occurs in almost all of the other samples analysed, although generally in smaller proportions.

Late Neoproterozoic detrital zircon (500-650 Ma, and even up to 850 Ma) is a major detrital component on both the eastern flank of the Andes and at Buill. Although it is absent from the Brazo Tronador and Lacui samples, both still have notable "Grenville" and older peaks. Detrital zircon in this age range is quite common throughout the South American margin of Gondwana (Ireland et al., 1998; Cawood et al., 1999; Goodge et al., 2004), and potential igneous sources may be found in the orogenic belts of eastern Brazil and, to some extent, the Sierras Pampeanas.

Ordovician detrital zircon comprises a prominent age peak in many samples, e.g., those from the Cushamen Formation on the Argentine side of the Andes, the Buill meta-sandstone and the HUI-T8 borehole core. Scarce detrital zircons of possible Ordovician age were also found at cuesta de Rahue and estero El Loco. Granite magmatism of this age (Famatinian) is well known throughout the proto-Gondwana margin of South America, extending from the northern Andes as far as the northeastern part of the North Patagonian Massif (Pankhurst et al., 2006, 2014; Varela et al., 2009).

5.2. Devonian zircon ages

Even though individual apparent ages as young as Carboniferous or Permian have been obtained, in many cases identification of post-470 Ma events is inconclusive since these ages are usually associated with high common Pb contents and possible subsequent Pb-loss. Nevertheless, Devonian ages of ca. 400 Ma obtained in scattered outcrops of metamorphic rocks cropping out at both sides of the main Andes, have given U-Pb zircon data consistent with them being Devonian country rocks affected by Devonian metamorphism and/or magmatism (Cruz Martínez et al., 2012; Hervé et al., 2016).

A Devonian age for deposition is fully established in the case of the Buill metasandstones by both fossil content and the age of 407±5 Ma for the youngest detrital zircon component. Our data from all the other samples analysed are consistent with a similar sedimentary age (if a very few younger ages with high common Pb contents are discounted as noted above). A few kilometres south of Buill, on the southern shore of Reñihue fjord, a Middle Devonian (388±2 Ma) detrital zircon maximum depositional age was obtained in a fine-grained metasandstone (Fig. 7A and B), which is found between a thick pile (km wide) of pillowed metabasalt, parts of the stratigraphic section interpreted as tectonically inverted (Fig 7C and D). Given the oceanic nature of the metabasalts which are spatially associated to ultramafic rocks (Crignola, 1999; Hervé et al., 2017), and the proximity of these with the present-day location of the Chaitenia magmatic axis (Fig. 8), the turbidite-pillow basalt-ultramafic rocks associations cropping out at Reñihue fjord rise up as the most probable country rocks of the Devonian magmatism in the Chaitenia terrane, at these latitudes. At Lacui, in the Bahía Mansa metamorphic complex, a Devonian maximum possible sedimentation age was obtained for a metasandstone resembling those of the Llanquihue metamorphic complex (Hervé et al., 2016).

In the western edge of the North Patagonian Massif, Devonian detrital zircon (406±3 Ma) was obtained at río Lipinza (where it is far more evident than Ordovician provenance), and in two of the Cushamen Formation samples.

Two of the igneous rocks dated here are Devonian. On the basis of our data, the Zarao rhyolite could be as young as 382±3 Ma, but our preferred age estimate is 393±3 Ma, consistent both with the result of Duhart et al. (2001) and with our confirmed age of the Colán Conhue granite. These ages imply magmatism penecontemporaneous with the Emsian-Eifelian deposition of the Buill slate protolith, which contains slightly older detrital zircons (407±5 Ma). After Quezada (2015) and Vildoso (2017) the Zarao rhyolite is geochemically similar to siliceous alkaline differentiated rocks from oceanic islands or mid ocean ridges. If we consider that the Zarao rhyolite is at least ca. 5 My older than the oldest neighbouring metamorphic rocks (Fig. 2), then is reasonable to suggest that the Zarao rhyolite was not intruded into the accretionary prism, but was transported and tectonically emplaced in it.

On the other hand, U-Pb SHRIMP dating of zircon from other igneous intrusive rocks in the coastal metamorphic complex slightly east of Buill (Hervé et al., 2016) suggest continuation of magmatism and sedimentation in Chaitenia into Late Devonian times (Pichicolo 384±3 Ma, Chaitén 383±2 Ma, Centro del Mundo quarry 361±7 Ma).

Previous O and Hf isotope work (Hervé et al., 2016) has shown that Devonian detrital zircons in diverse Paleozoic metamorphic rock units in the present day coastal region at these latitudes, including probably Devonian metasedimentary rocks in the Llanquihue metamorphic complex at Los Muermos (Fig. 2), were derived from intrusive rocks of the kind that crop out in the Devonian continental arc on the eastern flank of the Andes rather than from the more primitive intrusive rocks in Chile, such as the Chaitenia arc-related plutons at continental Chiloe (Quezada et al., 2015) and the Zarao rhyolite (FO14175, Fig. 8). This interpretation is supported by the lack of a major zircon provenance differences in the east-west transect represented by this study, except for the different percentage of the Precambrian zircon grain age populations, which are more abundant in the North Patagonian Massif (76%) than in Chaitenia (25%).

Devonian metamorphism is especially clear in sample FO1527 from Brazo Tronador (lago Mascardi), where ca. 390 Ma metamorphic rims are developed on (mostly) Mesoproterozoic cores (Fig. 4). The petrographic evidence of Cruz Martínez et al. (2012) indicates that this Devonian metamorphism developed in situ in the original sedimentary protolith. No such metamorphic rims, nor the Carboniferous ones in sample FO1525, have been observed in the Chilean samples, suggesting that metamorphism was of lower grade farther west. If collision of a southern extension of the Chilenia terrane were responsible for this metamorphism (Cruz Martínez et al., 2012), then the latter would appear to consist mostly of post-Ordovician metasediments which is not compatible with the ages assigned to Chilenia (580-530 Ma; Álvarez et al., 2011). We prefer the concept of Chaitenia as an (initially) offshore Devonian island arc as suggested in Hervé et al., (2016) as the colliding body.

A post-470 Ma depositional age for the majority of these samples is established by the U-Pb data for detrital zircons, but in some cases a mid-Paleozoic age is confirmed by the fact that they are intruded by igneous rocks dated at 306±2 Ma (Cuesta de Rahue), penecontemporaneous with the Pennsylvanian Coastal Batholith of Chile (Deckart et al., 2014), and of the Devonian age in the granitic body intruding the rocks of the Llanquihue metamorphic complex (McDonough et al, written communication, 2001) at the ENAP borehole Rahue-2.

Finally, a tonalite intrusion into the basement north of Lago Nahuel Huapi has been dated at 184±2 Ma, suggesting that it may represent the northern extension to the Early Jurassic Subcordilleran batholith west of the North Patagonian Massif (Rapela et al., 2005).

The metasedimentary rocks dated here can be interpreted as part of a local backstop to the Carboniferous to Triassic accretionary complex of the coastal region. The scarcity and discontinuity of Devonian or older basement at the presently exposed crustal level result from its involvement in Late Paleozoic and Andean tectonic and magmatic processes.

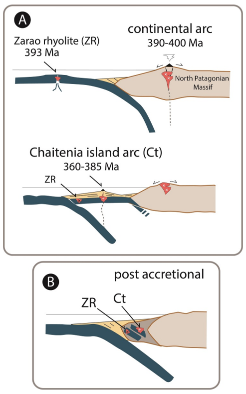

Fig. 8.

Fig. 8. A. Schematic cross sections showing the assumed relationships between the different Paleozoic tectonic units in the Gondwana margin at 41 to 42° S (present coordinates) at two different Devonian time slots. B. Schematic cross section showing main tectonic units at the same latitude, after assumed post Devonian accretion of Chaitenia to the Gondwana margin.

6. Conclusions

Scattered outcrops of metamorphic rocks in the Andean region and in the western part of the North Patagonian Massif have detrital zircon grains indicating that they were deposited during (or perhaps in some cases slightly before) Devonian times. Some samples show the effects of a Devonian metamorphic event, which has been previously assigned to the collision of Chilenia with Patagonia. Here we prefer to consider a collision of a separate oceanic island arc suspect terrane, Chaitenia, as suggested in Hervé et al. (2016) extending south of the Huincul lineament which is considered the southern limit of the Chilenia terrane by Ramos et al. (1986). Chaitenia plutonic rocks differ from the ones of the Devonian magmatic arc in the Patagonian Massif in the isotope geochemistry of zircon, and have different lithologies in their country rocks. However, a metasedimentary rock of Chaitenia, which is interbedded with pillow metabasalts (Fig. 7) shows no major provenance differences from those of the continental foreland, suggesting that the island arc formed in a proximal position to the Gondwana margin while magmatism was active (Fig. 8). These rocks constituted a backstop to the late Carboniferous -Triassic accretionary prism which extends further west.

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References

Álvarez, J.; Mpodozis, C.; Arriagada, C.; Salazar, E.; Morata, D.; Peña, M. 2009. Circones Detríticos del Complejo Metamórfico El Tránsito, Cordillera de Vallenar: ¿Evidencias acerca del basamento de Chilenia? In Congreso Geológico Chileno, No. 12: S9_001. Santiago.

Álvarez, J.; Mpodozis, C.; Arriagada, C.; Astini, R.; Morata, D.; Salazar, E.; Valencia, V.A.; Vervoort, J.D. 2011. Detrital zircons from late Paleozoic accretionary complexes in north-central Chile (28°-32° S): Possible fingerprints of the Chilenia Terrane. Journal of South American Earth Sciences 32: 460-476. doi: 10.1016/j.jsames.2011.06.002.

Álvarez, J.; Murillo, I.; Mpodozis, C. 2013a. U-Pb ages and metamorphic evolution of the La Pampa Gneisses and the Quebrada Seca Schists: implications for the evolution of the Chilenia Terrane and Permo-Triassic tectonics of North-Central Chile. Bolletino de Geofísica Teórica et Applicata 54, Supplement 2: 35-36.

Álvarez, J.; Mpodozis, C.; Blanco-Quintero, I.F.; García-Casco, A.; Morata, D.; Arriagada, C. 2013b. U/Pb geochronology and P-T-t path of the La Pampa Gneisses, implications for the evolution of the Chilenia Terrane and Permo-Triassic tectonics of North-Central Chile. Journal of South American Earth Sciences 47: 100-115.

Cawood, P.A.; Nemchin, A.A.; Leverenz, A.; Saeed, A.; Ballance, P.F. 1999. U/Pb dating of detrital zircons: implications for the provenance record of Gondwana margin terranes. Geological Society of America, Bulletin 111: 1107-1119.

Chernicoff, C.; Zappettini, O.; Santos, J.; McNaughton, N.; Belousova, E. 2013. Combined U-Pb SHRIMP and Hf isotope study of the Late Paleozoic Yaminué Complex, Río Negro Province, Argentina: implications for the origin and evolution of the Patagonia composite terrane. Geoscience Frontiers 4: 37-56.

Cohen, K.M.; Finney, S.C.; Gibbard, P.L.; Fan, J.X. 2013. The ICS international Chronostratigraphic Chart. Episodes 36: 199-204.

Crignola, P. 1999. Geología del Fiordo Reñihue y parte occidental de la Peninsula Huequi, Chiloé Continental, X Region, Chile. Memoria de Título de Geólogo (Unpublished), Universidad de Concepción: 115 p.

Cruz Martínez, J.; Dristas, J.A.; Massonne, H.-J. 2012. Palaeozoic accretion of the microcontinent Chilenia, North Patagonian Andes: high-pressure and subsequent thermal relaxation. International Geology Review 54: 472-490.

Dalla Salda, L.H.; Cingolani, C.; Varela, R. 1991. El basamento cristalino de la región norpatagónica de los lagos Gutiérrez, Mascardi y Guilllelmo, Provincia de Río Negro. Revista de la Asociación Geológica Argentina 46: 263-276.

Deckart, K.; Hervé, F.; Fanning, C.N.; Ramírez, V.; Calderón, M.; Godoy, E. 2014. U-Pb Geochronology and Hf-O isotopes of zircons from the Pennsylvanian Coastal Batholith, South-Central Chile. Andean Geology 41 (1) 49-82. doi: 10.5027/andgeoV41n1-a03.

Drabon, N.; Lowe, D.R.; Byerly, G.R.; Harrington, J.A. 2017. Detrital zircon geochronology of sandstones of the 3.6-3.2 Ga Barberton greenstone belt: No evidence for older continental crust. Geology 45 (9): 803-806.

Duhart, P.; McDonough, M.; Muñoz, J.; Martin, M.; Villeneuve, M. 2001. El Complejo Metamórfico Bahía Mansa en la Cordillera de la Costa del centro-sur de Chile 39°30"-42°00" S: geocronología K-Ar, Ar/Ar y U-Pb e implicancias en la evolución del margen sur-occidental de Gondwana. Revista Geológica de Chile 28 (2): 179-208. doi: 10.5027/andgeoV28n2-a03.

Fortey, R.; Pankhurst, R.J.; Hervé, F. 1992. Devonian trilobites at Buill, Southern Chile. Revista Geológica de Chile 19 (2): 133-144. doi: 10.5027/andgeoV19n2-a01.

García-Sansegundo, J.; Farías, P.; Gallastegui, G.; Giacosa, R.E.; Heredia, N. 2009. Structure and metamorphism of the Gondwana basement in the Bariloche region (North Patagonian Argentine Andes). International Journal of Earth Sciences 98: 1599-1608.

Godoy, E.; Hervé, F.; Fanning, C.M. 2008. Edades U-Pb SHRIMP en 38°S de granitoides del Macizo Norpatagónico: implicancias geotectónicas. In Congreso Geológico Argentino, No. 17, Actas 3: 1288-1289. San Salvador de Jujuy.

Goodge, J.W.; Williams, I.S.; Myrow, P. 2004. Provenance of Neoproterozoic and lower Paleozoic siliciclastic rocks of the central Ross orogen, Antarctica: Detrital record of rift-, passive-, and active-margin sedimentation. Geological Society of America, Bulletin 116: 1253-1279.

Hervé, F. 1988. Late Paleozoic subduction and accretion in Southern Chile. Episodes 11: 183-188.

Hervé, F.; Fanning, C.M.; Pankhurst, R.J. 2003. Detrital Zircon Age Patterns and Provenance of the metamorphic complexes of Southern Chile. Journal of South American Earth Sciences 16: 107-123.

Hervé, F.; Faúndez, V.; Calderón, M.; Massonne, H.-J.; Willner, A.P. 2007. Metamorphic and plutonic basement complexes. In The Geology of Chile (Moreno, T.; Gibbons, W.; editors), The Geological Society: 5-19. London.

Hervé, F.; Calderón, M.; Fanning, C.M.; Pankhurst, R.J.; Godoy, E. 2013. Provenance variations in the Late Paleozoic accretionary complex of central Chile as indicated by detrital zircons. Gondwana Research 23: 112-113.

Hervé, F.; Fanning, M.; Calderón, M.; Mpodozis, C.; 2014. Early Permian to Late Triassic batholiths of the Chilean Frontal Cordillera (28°-31°S): SHRIMP U-Pb zircon ages and Lu-Hf and O isotope systematic. Lithos 184-187: 436-446.

Hervé, F.; Calderón, M.; Fanning, C.M.; Pankhurst, R.J.; Fuentes, F.; Rapela, C.W.; Correa, J.; Quezada, P.; Marambio, C. 2016. Devonian magmatism in the accretionary complex of southern Chile. Journal of the Geological Society 173: 587-602. doi:10.1144/jgs2015-163. London.

Hervé, F.; Fuentes, F.; Calderón, M.; Fanning, C.M.; Quezada, P.; Pankhurst, R.J.; Rapela, C.W. 2017. Ultramafic rocks in the North Patagonian Andes: is their emplacement associated with the Neogene tectonics of the Liquiñe-Ofqui Fault Zone? Andean Geology 44 (1): 1-16. doi: 10527/andeangeov44n1-a01.

Ireland, T.R.; Flötmann, T.; Fanning, C.M.; Gibson, G.M.; Preiss, W.V. 1998. Development of the early Paleozoic Pacific margin of Gondwana from detrital-zircon ages across the Delamerian orogen. Geology 26: 243-246.

Levi, B.; Aguilar, A.; Fuenzalida, R. 1966. Reconocimiento geológico en las provincias de Llanquihue y Chiloé. Instituto de Investigaciones Geológicas, Boletin 19: 45 p. Santiago.

Ludwig, K.R. 2003. Isoplot 3.0 A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center, Special Publication 4: 70 p.

McDonough, M.; Ugalde, H.; Duhart, P.; Crignola, P. 1997. Nuevos antecedentes estructurales de la Cordillera de la Costa y el adyacente Valle Central en la parte norte de la X Región, Chile: su relación con el patrón magnético. In Congreso Geológico Chileno, No. 8, Actas 1: 169-172. Antofagasta.

Ostera, H.A.; Linares, E.; Haller, M.J.; Cagnoni, M.C.; López de Luchi, M. 2001. A widespread metamorphic Devonian episode in Northern Patagonia, Argentina. In South American Symposium on Isotope Geology, No. 3, Actas CD: 52, Resúmenes: p. 161. Santiago.

Pankhurst, R.J.; Rapela, C.W.; Fanning, C.M.; Márquez, M. 2006. Gondwanide continental collision and the origin of Patagonia. Earth-Science Reviews 76: 235-257.

Pankhurst, R.J.; Rapela, C.W.; López de Luchi, M.G.; Rapalini, A.E.; Fanning, C.M.; Galindo, C. 2014. The Gondwana connections of Patagonia. Journal of the Geological Society 171: 313-328.

Quezada, P. 2015. Geología del basamento de la Región de Los Lagos, Chile: evidencias de magmatismo calco alcalino y aportes sedimentarios devónicos. Graduation thesis (Unpublished), Universidad de Chile, Departamento de Geología: 105 p. Santiago.

Quezada, P.; Hervé, F.; Calderón, M.; Fuentes, F.; Fanning, C.M.; Pankhurst, R.J.; Rapela, C.W.; Correa, J. 2015. Contrasting magmatic sources of Devonian calc-alkaline magmatism emplaced in the western slope of the Andes, Chile, and North Patagonian Massif, Argentina (40-43°S Lat.). In Congreso Geológico Chileno, No. 14 (Charrier, R.; Hervé, F.; Maksaev, V.; Mpodozis, C.; Oyarzún, J.; editors): ST3_066. La Serena.

Ramos, V.A.; Jordan, T.; Allmendinger, R.; Kay, S.M.; Cortés, J.M.; Palma, M.A. 1984. Chilenia: un terreno alóctono en la evolución paleozoica de los Andes Centrales. In Congreso Geológico Argentino, No 9, Actas 2: 84-106. San Carlos de Bariloche.

Ramos, V.A.; Jordan, T.E.; Allmendinger, R.W.; Mpodozis, C.; Kay, S.M.; Cortés, J.; Palma, M. 1986. Paleozoic terranes of the Central Argentine Chilean Andes. Tectonics 5: 855-880.

Ramos, V.; García-Morabito, E.; Hervé, F.; Fanning, C.M. 2010. Grenville age sources in Cuesta de Rahue, Northern Patagonia: constrains from U-Pb SHRIMP ages from detrital zircons. Geosur 2010, Bolletino di Geofísica teórica ed applicata 51 (supplement): 42-45. Mar del Plata.

Rapela, C.W.; Pankhurst, R.J.; Fanning, C.M.; Hervé, F. 2005. Pacific subduction coeval with the Karoo mantle plume: the Early Jurassic Subcordilleran belt of northwestern Patagonia. In Terrane Processes at the Margins of Gondwana (Vaughan, A.P.M.; Leat, P.T.; Pankhurst, R.J.; editors), Geological Society, Special Publication 246: 217-240.

Rapela, C.W.; Verdecchia, S.O.; Casquet, C.; Pankhurst, R.J.; Baldo, E.G.; Galindo, C.; Murra, J.A.; Dahlquist, J.A.; Fanning, C.M. 2016. Identifying Laurentian and SW Gondwana sources in the Neoproterozoic to

Early Paleozoic metasedimentary rocks of the Sierras Pampeanas: paleogeographic and tectonic implications. Gondwana Research 32: 198-212: doi: 10.1016/j.gr.2015.02.010.

SERNAGEOMIN, 2003. Mapa geológico de Chile, versión digital. Servicio Nacional de Geología y Minería, Publicación Geológica Digital, No. 4 CD-Room, versión 1.0, base geológica escala 1:1.000.000.

Varela, R.; Cingolani, C.A.; Passarelli, C.R.; Basei, M.A.S. 2005. El basamento cristalino de los Andes Norpatagónicos en Argentina: geocronología e interpretación tectónica. Revista Geológica de Chile 32 (2): 167-187. doi: 10.5027/andgeoV32n2-a01.

Varela, R.; Sato, K.; González, P.D.; Sato, A.M.; Basei, M.A.S. 2009. Geología y geocronología Rb-Sr de granitoides de Sierra Grande, Provincia de Río Negro. Revista de la Asociación Geológica Argentina 64: 275-284.

Vildoso, M.F. 2017. Petrología del basamento metavolcánico Devónico de la Cordillera del Zarao, Los Muermos, Región de los Lagos, Chile. Graduation thesis (Unpublished), Universidad de Andrés Bello, Carrera de Geología: 67 p. Santiago.

Williams, I.S. 1998. U/Th/Pb geochronology by ion microprobe. In Applications of microanalytical techniques to understanding mineralizing processes. (McKibben, M.A.; Shanks, W.C.; Ridley, W.I.; editors) Reviews in Economic Geology 7: 1-35.