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The South American ancestry of the North Patagonian Massif: geochronological evidence for an autochthonous origin?

Augusto E. Rapalini,[1] Mónica López de Luchi,[2] Eric Tohver[3] and Peter A. Cawood[3,4]

[1]*Instituto de Geociencias Básicas, Aplicadas y Ambientales de Buenos Aires (IGEBA), Dept. Cs. Geológicas, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires-CONICET, Pabellón 2, Ciudad Universitaria, Buenos Aires, C1428EHA, Argentina;* [2]*Instituto de Geocronología y Geología Isotópica (INGEIS), Universidad de Buenos Aires-CONICET, Ciudad Universitaria, Buenos Aires, Argentina;* [3]*School of Earth and Environment, University of Western Australia - M004, 35 Stirling Hwy, Crawley Western Australia, 6009, Australia;* [4]*Department of Earth Sciences, University of St. Andrews Fife, KY16 9AL, Scotland, UK*

ABSTRACT

New U-Pb and $^{40}Ar/^{39}Ar$ age data from deformed and undeformed granitoids of the North Patagonian Massif establish the presence of Early Cambrian and widespread Ordovician magmatism in northern Patagonia. These data suggest that the Pampean (Cambrian) and Famatinian (Ordovician) magmatic belts of the Sierras Pampeanas are continuous into Patagonia. SHRIMP U-Pb age spectra from detrital zircons of Cambro-Ordovician metasedimentary rocks show patterns very similar to those from equivalent units of the Pampia block, over 500 km farther north. These results suggest that the North Patagonian Massif was likely part of the South American margin of Gondwana in the early Palaeozoic and strongly argue in favour of an authochtonous or para-autochthonous origin for this block.

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Introduction

A long-standing debate over the origin of Patagonia revolves around whether the basement rocks constitute a geological province of ancestral South America or form an exotic terrane accreted in the Late Palaeozoic (see Cawood, 2005; Pankhurst *et al*., 2006; Ramos, 2008; Rapalini *et al*., 2010 and references therein). Pankhurst *et al*. (2006) determined the Ordovician age of small and undeformed plutons exposed near the northern Patagonia shoreline and suggested that they were part of a continuous Ordovician (Famatinian) magmatic arc extending from northern Argentina to northern Patagonia. Similarly, Martinez Dopico *et al*. (2011) presented isotopic evidence that suggests a strong correlation of the basements of the Sierras Pampeanas (Pampia) and the North Patagonia Massif (NPM). However, the allochthonous origin for Patagonia, originally suggested by Ramos (see Ramos, 2008), has recently been supported by González *et al*. (2011) who reported Early Cambrian Archeocyatids in the NPM that resemble taxa in the TransAntarctic Mountains, suggesting that Patagonia originated in a margin-parallel location more than 2500 km from South America (see also Dalziel *et al*., 2013, for a different interpretation)

We test the tectonic models for Patagonia by obtaining new geochronological data on igneous units exposed in the NPM. Our results provide the first evidence of Early Cambrian plutonic activity in northern Patagonia and the existence of voluminous magmatism during the Ordovician.

Correspondence: Augusto Ernesto Rapalini, Instituto de Geociencias Básicas, Aplicadas y Ambientales de Buenos Aires (IGEBA), Dept. Cs. Geológicas, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires-CONICET, Pabellón 2, Ciudad Universitaria, Buenos Aires, C1428EHA Argentina. Tel.: 54 11 4788 3439; fax: 54 11 4788-3439; e-mail: rapalini@gl.fcen.uba.ar

Geological background

The basement of Patagonia is subdivided into the NPM, in the north, and the Deseado Massif in the south (Fig. 1). The northern boundary of NPM with the Pampia and Cuyania terranes is covered by the Meso-Cenozoic Colorado Basin. The most conspicuous basement units are Early Palaeozoic metasedimentary rocks with variable metamorphic grades. From east to west, they are the low-grade metasediments of the El Jagüelito Formation, the high-grade Mina Gonzalito Complex and the low to medium-grade Nahuel Niyeu Formation. In our study area, only the latter is exposed (Fig. 1). Ordovician igneous rocks intrude the metasedimentary successions (Gozálvez, 2009). West of Valcheta (Fig. 1), strongly deformed granodiorite-monzogranite orthogneiss, known as the Tardugno Granodiorite, is intruded by the Late Palaeozoic Navarrete Plutonic Complex (see Lopez de Luchi *et al*., 2010 and references therein) and the Triassic–Early Jurassic Treneta Plutonic and Volcanic complex. The Tardugno Granodiorite is locally intruded by an undeformed tonalite dated by Basei *et al*. (2002) at 300 ± 6 Ma (multi-grain U-Pb) and attributed to the granodiorite, although its undeformed fabric suggests that it is a part of the Navarrete Plutonic Complex.

The Nahuel Niyeu Formation, made up of meta-sandstones/siltstones, phyllites and metavolcaniclastic rocks, is in tectonic contact with the Tardugno Granodiorite. Graded and cross-bedding are preserved in the meta-sandstones, which are texturally immature, quartz- and microcline-rich, suggesting a proximal granitic source. Metamorphic grade reaches middle/upper greenschist facies in the East (Martinez Dopico *et al*., 2011).

The Yaminué Complex (see Lopez de Luchi *et al*., 2010 and references

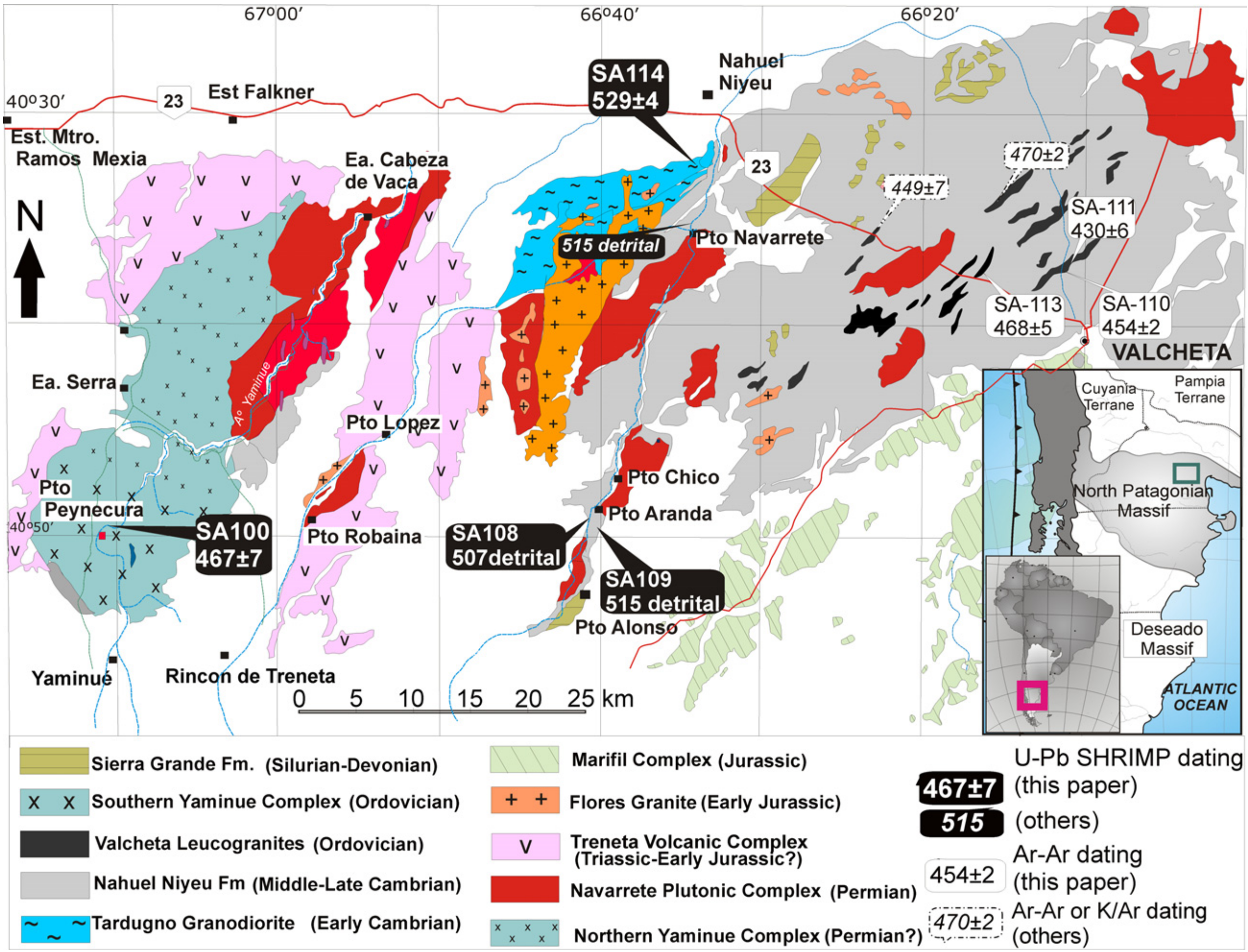

Fig. 1 Geological map of the region west of the town of Valcheta with indication of geochronological data obtained in this and previous studies. In the inset, location of the study area in the North Patagonian Massif. Modified from Lopez de Luchi *et al.* (2010).

therein) lies in the west of the Tardugno Granodiorite (Fig. 1) and consists of shallowly dipping, sheet-like bodies of a synkinematic foliated, coarse to medium-grained, porphyritic granodiorite-monzogranite plus minor amounts of tonalite. Abundant sub-concordant sheets of a fine-grained leucogranite are intercalated with the granodiorite-monzogranite (Lopez de Luchi *et al*., 2010). Small inliers of marble and rare amphibolite are found to the south of these outcrops (Fig. 1). Multi-grain conventional U-Pb ages on zircons from this unit (Basei *et al*., 2002) range from 305 to 244 Ma. A Late Permian age (261 Ma) has been reported very recently (Chernicoff *et al*., 2013) from central areas of the complex (U-Pb SHRIMP in zircon).

Results

Our study was carried out on the deformed Tardugno Granodiorite and Yaminué Complex by SHRIMP U-Pb dating of magmatic zircons. Detrital zircons from the Nahuel Niyeu Formation were dated to constrain the source region for these clastic rocks. The undeformed leucogranitic plutons that intrude the Nahuel Niyeu Formation were dated to assess the regional thermal history (Figs 1 and 2). Detailed analytical results are presented in Tables S1 and S2 (see Supporting Information) and illustrated in Fig. 2. Laboratory facilities and procedures are those described in Tohver *et al*. (2012b).

The zircon population of the Tardugno granodiorite (sample SA114, 40°33.2′S, 66°33.9′W) is homogeneous and unimodally distributed around the mean $^{238}U/^{206}Pb$ age of 528.5 ± 3.5 Ma (Fig. 2A, Table S1), with the exception of two inherited grains of *c*. 610 Ma that are overgrown by ~530 Ma zircon rims. With the exception of one zircon grain, all analyses were concordant with tightly clustered Th/U ratios of 0.2–0.5.

Zircons from a foliated granodiorite of the southern Yaminué complex (sample SA100, 40°50.2′S, 67°11.4′W) are clear and euhedral with oscillatory to sector zonation under cathodoluminescence. A wide range of Th/U ratios is observed (0.1–1.2), but there is no corresponding range of $^{238}U/^{206}Pb$ ages, with a mean age of 467 ± 7 Ma (Fig. 2B). Two ~530 Ma grains are interpreted as inherited material.

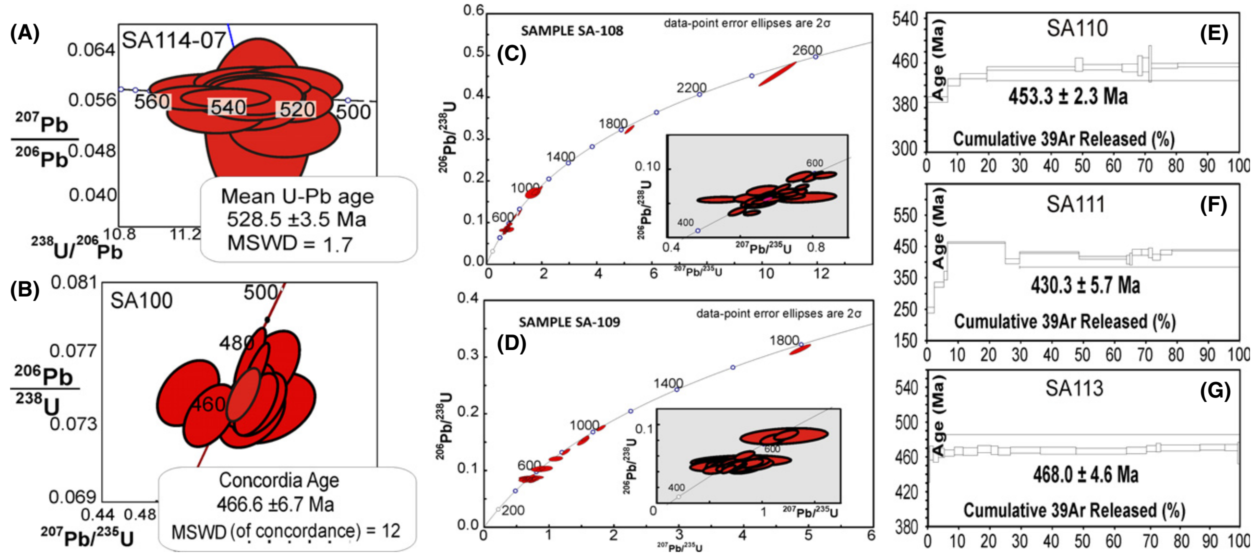

Fig. 2 (A) concordia plot for magmatic zircons of the Tardugno Granodiorite, (B) idem for the southern Yaminué complex, (C, D) concordia plots for detrital zircons of samples from the Nahuel Niyeu Formation, (E, F and G) $^{39}Ar/^{40}Ar$ stepwise plateau diagrams for samples from the leucogranites west of Valcheta. Details of the analytical results are presented in Tables S1 and S2.

Samples SA-108 (40°48.6′S, 66°40.2′W) and SA-109 (40°49.0′S, 66°40.2′W) from metapsammites of low metamorphic grade of the Nahuel Niyeu Formation were collected from nearby outcrops (Fig. 1). Variably rounded quartz clasts, and scarce feldspar and polycrystalline quartz clasts are set in a fine-grained matrix composed of clay minerals, sericite, opaque minerals and chlorite. The detrital zircon populations from both samples are similar, dominantly euhedral with some grains that are slightly rounded. The U/Pb ages from these detrital grains are predominantly *c.* 530 Ma, with a small population of *c.* 1.0 Ga material (Figs 2 and 4).

Samples of the muscovite-bearing leucogranites vary in texture from medium to fine grained and are equigranular, with no macroscopic evidence of strain or fabric development. Three samples (Fig. 1), SA-110 (40°37.3′S, 66°11.4′W), SA-111 (40°37.4′S, 66°12.0′W) and SA-113 (40°37.7′S, 66°18.2′W), were dated by the ^{39}Ar-^{40}Ar method on magmatic muscovites to ascertain the age and timing of regional cooling. All three samples yielded well-behaved plateau ages of 453 ± 2, 430 ± 6 and 468 ± 5 Ma (Fig. 2 E, F, G, Table S2), similar to the 467 Ma age of the southern Yaminué Complex crystallization, suggesting a regional cooling through the muscovite blocking temperature (400 °C) during Late Ordovician to Silurian.

Discussion and interpretation

The age of 528.5 ± 3.5 Ma for the Tardugno Granodiorite is the first reported evidence for Cambrian magmatism in the North Patagonian Massif. Thus, the large amounts of Early Cambrian zircons in Middle to Upper Cambrian metasedimentary rocks of northern Patagonia (Fig. 4) could have been derived from local sources. Fig. 3A shows that Early Cambrian (*c.* 550–520 Ma) calcalkaline magmatism (mainly plutons) in central Argentina forms a long belt from Sierra Norte in the Cordoba province (Schwartz *et al.*, 2008) to the Chadileuvu block in the La Pampa province (Chernicoff *et al.*, 2012). This belt has been interpreted as a magmatic arc located along the eastern margin of the Pampia terrane (Ramos *et al.*, 2010). The Tardugno Granodiorite represents a further southern extension of this magmatic belt.

Our age for the southern part of the Yaminué Magmatic Complex of 467 ± 7 Ma (Fig. 3B) for both zircon cores and rims contrasts with the recently reported Late Permian age for a sample from central areas of this complex (Chernicoff *et al.*, 2013). This suggests that the complex may include Ordovician southern and Late Palaeozoic northern components. Undeformed latest Permian granitic dykes intruding our sample site (Tohver *et al.*, in preparation) are consistent with this interpretation. The Ordovician age, intense deformation and the presence of marbles in the host of the granitoids suggest a correlation between the southern Yaminué Magmatic Complex and Ordovician intrusive rocks of the Mina Gonzalito Complex (Giacosa, 1997). SHRIMP U-Pb age of zircons from a granodioritic orthogneiss of the latter yielded an age of 492 ± 6 Ma (Varela *et al.*, 2011). The metamorphic overprint of this complex has been dated at 472 ± 5 Ma (Pankhurst *et al.*, 2006; Fig. 3B), coeval with the synkinematic intrusion of the southern Yaminué Magmatic Complex. Farther to the East, the small El Molino pluton has also been dated as Ordovician (472 ± 5 Ma, González *et al.*, 2008).

Middle to Late Ordovician (450–470 Ma) cooling ages for the undeformed peraluminous leucogranites exposed to the west of Valcheta (Fig. 1) were obtained by López de Luchi *et al.* (2008) and Gozálvez (2009) by K-Ar and Ar-Ar on

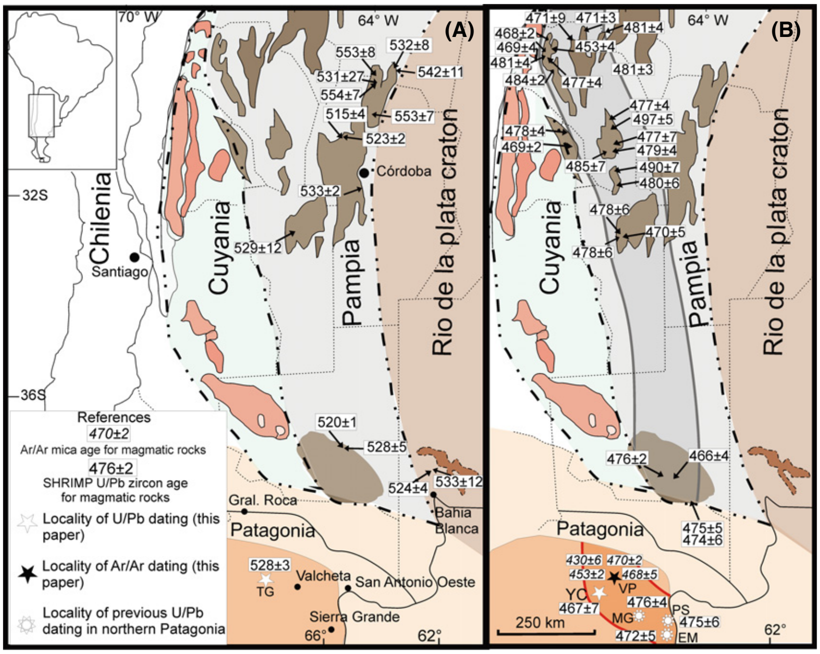

Fig. 3 (A) Main tectonic terranes of central Argentina and northern Patagonia and distribution of Early Cambrian (Pampean) magmatic rocks (simplified from Ramos *et al.*, 2010; Chernicoff *et al.*, 2012; Tohver *et al.*, 2012a). Star shows location of the dated Tardugno Granodiorite. (B) Idem A with plot of main outcrops of Ordovician (Famatinian) magmatic belt (shaded) and distribution of coeval magmatic rocks in the North Patagonian Massif. Stars show location of dated rocks.

muscovite respectively. We have obtained three additional good quality ^{39}Ar-^{40}Ar cooling ages in muscovite in the range 430–470 Ma. These ages and the undeformed nature of the plutons suggest that they are likely part of a widespread Ordovician magmatism in the NPM. The 30-Ma interval may represent either a very slow cooling history or a protracted Ordovician to Early Silurian magmatism in the region. In any case, these cooling ages attest to the absence of reheating by regional metamorphism of these bodies since Silurian times.

The southern Yaminué, Mina Gonzalito, El Molino and the Valcheta leucogranites, plus the undeformed Punta Sierra Complex (Fig. 2G), exposed close to the Atlantic coast and dated at 475 Ma (U-Pb SHRIMP, Pankhurst *et al.*, 2006), likely represent a magmatic arc that is a continuation of the Famatinian magmatic belt of central Argentina (Fig. 3B).

The crustal signature of the Valcheta plutons (unpublished data) is consistent with their location farther away from a hypothetical continental margin to the south and west. On the other hand, the chemical signature of most of the Punta Sierra granitoids indicates mafic magmatic input consistent with a location closer to the inferred margin.

Our samples of the Nahuel Niyeu Formation show a single dominant peak of detrital grains with Early Cambrian ages and subordinate peaks of *c.* 0.6, 0.7–0.8 and 1–1.1 Ga (Fig. 4). The youngest zircons suggest maximum depositional ages of ~510 Ma, coeval to that determined by Pankhurst *et al.* (2006) from a sample 25 km north of our sites (Figs 1 and 4). Age spectra of detrital zircons from all three localities are quite similar, although in our samples, the Precambrian peaks are less developed. The Nahuel Niyeu Formation spectra are very similar to those from other Early Palaeozoic metasedimentary rocks of the NPM (El Jagüelito and Mina Gonzalito Formations, Fig. 4), suggestive of common sources.

Conclusions

The Early Cambrian magmatism in NPM, represented by the Tardugno Granodiorite, correlates with the Pampean magmatic belt of central Argentina. Geographical distribution of these magmatic rocks in northern Patagonia is yet unknown; however, continuation of the Pampean magmatic arc there is now supported (Fig. 3A). The Ordovician magmatism is more widely distributed in NPM than previously envisaged. It seems to represent a curved and wide magmatic belt with a NW–SE trend (Fig. 3B) and a continental margin to the west and south. The outermost outcrops of this belt are defined by the tectonically deformed southern Yaminué, Mina Gonzalito and, possibly, El Molino plutons. The inner belt is made up by isolated outcrops of mainly undeformed plutons with abundant leucogranites (Valcheta granitoids), located over 100 km further away from the hypothetical continental margin. Fig. 3B shows the relative locations of the Famatinian arcs on Pampia and NPM. The inferred polarity of subduction and age of magmatism are identical between NPM and the central Argentina belt, across a relative displacement of *c.* 100 kilometres, which might have occurred during the opening of the South Atlantic (e.g. Torsvik *et al.*, 2008) or in the Late Palaeozoic (Rapalini *et al.*, 2010).

The Upper Cambrian metasedimentary units that overlie the NPM basement are marked by the same age populations that occur in similar units in the Pampean belt. The dominance of Pampean-aged material in all of these sediments suggests a similar provenance for Cambro-Ordovician sediments in both regions. The development of coeval basins and similar sources (Steenken *et al.*, 2006; Rapela *et al.*, 2007; Collo *et al.*, 2009; Fig. 4) support crustal continuity between the NPM and Pampia by Cambrian times. Similar conclusions were obtained recently by Uriz *et al.* (2011) from a comparison of the detrital zircon age patterns of Mid-Palaeozoic successions in the Rio de la Plata craton and northern Patagonia. If a N–S to NW–SE (present-day coordinates) active margin existed across central NPM in the Early Palaeozoic, growth of this terrane to the West by accretionary processes associated with East- and/

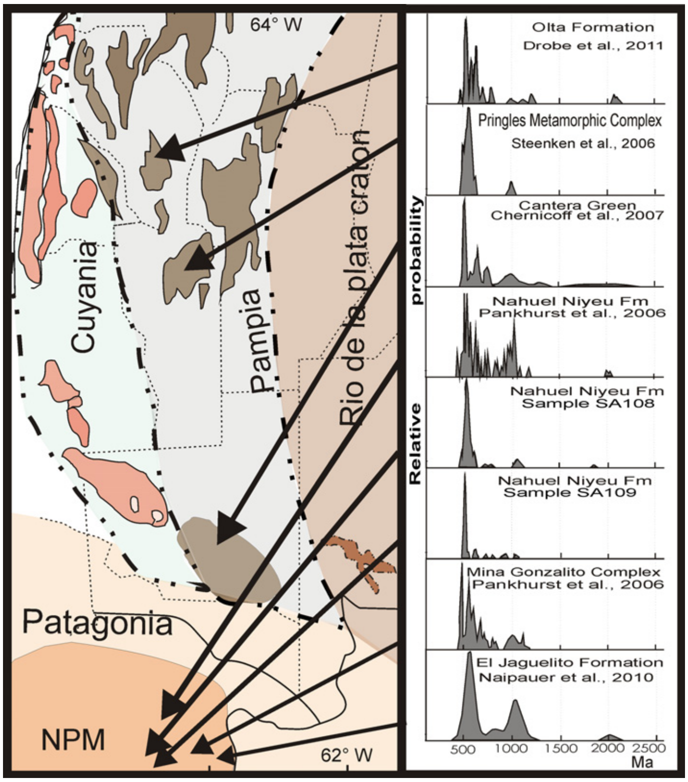

Fig. 4 Detrital zircon age patterns for Cambrian metasediments from the Sierras Pampeanas and the North Patagonian Massif, including those reported in this study, and their locations.

or North-directed subduction during the Palaeozoic is likely. If eastern NPM is a crustal fragment of Pampia, a section of the Cuyania's crust might be present in the subsurface of central NPM.

Based on Archeocyatid fossils found in the NPM, González *et al.* (2011) proposed that this block was close to the TransAntarctic Mountains in Cambrian times. The North Patagonian Ordovician Magmatic Belt was active until at least 470 Ma (and could potentially outlast this age). This magmatic belt is younger than the largely 530–490 Ma magmatism of the Ross Orogen (Goodge *et al.*, 2004), making correlation between the two unlikely. Strong tectonic deformation as observed in the southern Yaminué and Mina Gonzalito complexes is absent in the TransAntarctic Mountains, but present along the Famatinian arc. Models that propose the origin of the NPM in the TransAntarctic Mountains should explain these inconsistencies. Spagnuolo *et al.* (2012) proposed that Pampia was located close to Kalahari in Cambrian times. This palaeogeographical reconstruction might explain the Archeocyatids similarities because it indicates a location of an "autochthonous" NPM closer to East Antarctica than in traditional Gondwana reconstructions.

A major orogenic event that affected northern Patagonia and southern Pampia and Rio de la Plata craton in the Late Palaeozoic has been at the base of models of an allochthonous origin for the NPM (see Ramos, 2008 and references therein). In such models, this event was interpreted as a frontal collision between NPM and South American Gondwana. Non-collisional interpretations for such orogen (e.g. Dalziel *et al.*, 2000; Cawood, 2005; Pankhurst *et al.*, 2006 and references therein) have been proposed that would be consistent with the autochthonous origin proposed here. Furthermore, a para-autochthonous origin, as proposed by Rapalini *et al.* (2010), in which the NPM rifted away from southern Gondwana in the Middle Palaeozoic to collide back again in the Late Palaeozoic would agree with both the autochthonous origin and the collisional scenario.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Analytical data of U/Pb dating of magmatic and sedimentary circons in rocks from the Tardugno and Yaminué granitoids as well as the sedimentary successions of the Nahuel Niyeu Formation. More references in the text.

Table S2. Analytical data of Ar/Ar dating on muscovites from three plutons of the Valcheta granite. References and discussion in the text.

