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Crustal segments in the North Patagonian Massif, Patagonia: An integrated perspective based on Sm–Nd isotope systematics

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A B S T R A C T

New insights on the Paleozoic evolution of the continental crust in the North Patagonian Massif are presented based on the analysis of Sm–Nd systematics. New evidence is presented to constrain tectonic models for the origin of Patagonia and its relations with the South American crustal blocks. Geologic, isotopic and tectonic characterization of the North Patagonian Massif and comparison of the Nd parameters lead us to conclude that: (1) The North Patagonian Massif is a crustal block with bulk crustal average ages between 2.1 and 1.6 Ga T_{DM} (Nd) and (2) At least three metamorphic episodes could be identified in the Paleozoic rocks of the North Patagonian Massif. In the northeastern corner, Famatinian metamorphism is widely identified. However field and petrographic evidence indicate a Middle to Late Cambrian metamorphism pre-dating the emplacement of the ca. 475 Ma granitoids. In the southwestern area, are apparent 425–420 Ma (?) and 380–360 Ma metamorphic peaks. The latter episode might have resulted from the collision of the Antonia terrane; and (3) Early Paleozoic magmatism in the northeastern area is coeval with the Famatinian arc. Nd isotopic compositions reveal that Ordovician magmatism was associated with attenuated crust. On the southwestern border, the first magmatic recycling record is Devonian. Nd data shows a step by step melting of different levels of the continental crust in the Late Palaeozoic. Between 330 and 295 Ma magmatism was likely the product of a crustal source with an average 1.5 Ga T_{DM} (Nd). Widespread magmatism represented by the 295–260 Ma granitoids involved a lower crustal mafic source, and continued with massive shallower-acid plutono volcanic complexes which might have recycled an upper crustal segment of the Proterozoic continental basement, resulting in a more felsic crust until the Triassic. (4) Sm–Nd parameters and detrital zircon age patterns of Early Paleozoic (meta)-sedimentary rocks from the North Patagonian Massif and those from the neighboring blocks, suggest crustal continuity between Eastern Sierras Pampeanas, southern Arequipa-Antofalla and the northeastern sector of the North Patagonian Massif by the Early Paleozoic. This evidence suggests that, at least, this corner of the North Patagonian Massif is not allochthonous to Gondwana. A Late Paleozoic frontal collision with the southwestern margin of Gondwana can be reconcilied in a para-autochthonous model including a rifting event from a similar or neighbouring position to its post-collision location. Possible Proterozoic or Early Paleozoic connections of the NPM with the Kalahari craton or the western Antartic blocks should be investigated.

R E S U M E N

Se presenta una nueva perspectiva en el estudio en la evolución de la corteza cortinental durante el Paleozoico en el Macizo Norpatagónico, basada en el análisis de los parámetros isotópicos de Sm–Nd. Estas evidencias que constriñen los modelos tectónicos previamente propuestos explican el origen de Patagonia y su relación con el resto de los bloques corticales sudamericanos. La caracterización geológica, isotópica y tectónica del Macizo Norpatagónico y el estudio de los parámetros del sistema isotópico de Nd nos lleva a concluir que: (1) el Macizo Norpatagónico es un bloque cortical con una edad promedio de residencia cortical de entre 2.1 a 1.6 Ga T_{DM} (Nd) desde al menos el Paleozoico temprano; (2) En su basamento se pueden identificar al menos tres eventos metamorficos. En el borde noreste, se reconoce

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ampliamente la presencia de un evento metamórfico Famatiniano. Sin embargo, evidencias de campo y petrograficas indicarían un evento metamórfico Cámbrico medio a tardío que predataría el emplazamiento de los granitos ca. 475 Ma. En el sector suroccidental, hay indicios sobre un aparente metamorfismo entorno al período 425–420 Ma (?) y otro, mejor definido alrededor de 380–360 Ma; Este último episodio de metamorfismo resultaría de la colisión del terreno Antonia; (3) Si bien persiste una gran incertidumbre sobre los eventos magmáticos paleozoicos en el Macizo Norpatagónico, el magmatismo paleozoico temprano en el área noreste es coetáneo con el magmatismo Famatiniano en el resto del margen de Gondwana. Evidencias isotópicas de Nd revelan que en el Macizo Norpatagónico, este magmatismo ordovícico se habría producido sobre una corteza atenuada. En el sector suroeste, el primer registro de magmatismo atribuible al reciclaje cortical es Devónico. El análisis de los datos de los isótopos de Nd permite distinguir un proceso de fusión en etapas de diferentes segmentos de la corteza continental durante el Paleozoico tardío. El magmatismo producido entre los 330–295 Ma presenta signaturas corticales con una edad de residencia cortical de 1.5 Ga T_{DM} (Nd). Resultados sobre el extenso magmatismo pérmico 295–260 Ma indican que el primer segmento que se habría fundido de la corteza habría estado ubicado en la base de la corteza y habría tenido características geoquímicas máficas. Luego habría sobrevenido el reciclaje, fusión y mezcla con una corteza Proterozoica más somera, como lo evidencian los complejos plutonovolcánicos ácidos del Pérmico tardío a Triásico temprano; (4) La signatura isotópica obtenida por el método de Sm–Nd y los espectros de edades detríticas de circones de las rocas (meta) sedimentarias del Paleozoico inferior del Macizo Norpatagónico y aquéllas de los bloques vecinos sugieren la continuidad cortical entre las Sierras Pampeanas Orientales, el sector sur del bloque Arequipa-Antofalla y parte del sector noreste del Macizo Norpatagónico para el Paleozoico temprano. Por todas estas razones se postula que, al menos, este sector del el Macizo Norpatagónico no sería alóctono al Gondwana. La debatida hipótesis sobre una colisión frontal con el borde suroeste de Gondwana durante el Paleozoico superior puede ser reconciliada en un modelo que involucre la parautoctonía y que incluya un evento de rifting desde una posición similar o vecina a su ubicación post-colisión. Por último, se sugiere que próximas líneas de investigación deberían abordar las posibles conexiones del Macizo Norpatagónico durante el Proterozoico o Paleozoico temprano con el craton del Kalahari o los bloques de Antártida Occidental.

1. Introduction

Sm–Nd isotope signatures are widely used to decipher crustal formation and intracrustal processes. Via careful assessment of intracrustal processes active in certain areas they could be used to define terrane boundaries by determining isotope domains as indicators of both source reservoirs for magmatism and average age of crustal provinces (Bennett and DePaolo, 1987; De Paolo et al., 1991; Bock et al., 2000; Murphy and Nance, 2002; Cheng and Jahn, 1998; Loewy et al., 2004). In this approach we interpret Nd model ages not as ages for real crust formation following Arndt and Goldstein (1987). Nevertheless they provide a lower limit for the age of the involved crustal component (Klaine et al., 2004).

Different tectonic and paleogeographic scenarios have been proposed for the Paleozoic evolution of Patagonia that has been interpreted either as an allochthonous terrane accreted to the southwestern margin of Gondwana during the Late Paleozoic (Ramos, 1984, 2008; von Gosen, 2003; Chernicoff and Zappettini, 2003) or as (para-)autochthonous block that belonged to Gondwana since the Early Paleozoic (e.g. Dalla Salda et al., 1990, 1992; Rapalini, 1998, 2005; Rapalini et al., 2010). Pankhurst et al. (2006) recently suggested that while in Ordovician times the North Patagonian Massif was already part of Gondwana, southern Patagonia (Deseado Massif) constituted an allochthonous terrane that collided with the North Patagonian Massif during Mid Carboniferous times. Ramos (2008) (and references therein) suggested a collision between the Deseado Massif and NPM, but according to his model, the Deseado Massif plus the Antarctic Peninsula, also known as “Antonia” Terrane (Antarctic Peninsula plus Patagonia, Rapalini et al., 2010), collided the North Patagonian Massif in the Early to Middle Carboniferous. Subsequently, the combined terranes accreted onto Gondwana in the Late Carboniferous-Early Permian. Based on a multidisciplinary study Rapalini et al. (2010) hypothesized about the autochthony of northern Patagonia considering the continuity of the Pampean basement on the North Patagonian Massif. These authors proposed the marine sediments of the Siluro-Devonian Sierra Grande Formation as remnant of a small ocean, perhaps as an aulacogen, along the eastern part of original suture zone of the Pampia and North Patagonian Massif with the Río de la Plata Craton.

Tectonic models (Dalla Salda et al., 1990; Pankhurst et al., 2006; Ramos, 2008; Gregori et al., 2008; Rapalini et al., 2010, among others) discussing the relationship between Northern Patagonia and Gondwana have so far not systematically studied crustal signatures or growth events in the North Patagonian Massif and its neighbouring Gondwana blocks. Scarce and disconnected isotope data has for many years hindered detailed studies of crustal domains present within the North Patagonian Massif, in spite of a group of well established radiometric ages and isotopic studies.

In this study we integrate new and published Sm–Nd isotope data for the main Paleozoic and Triassic magmatic, sedimentary and metamorphic events in the North Patagonian Massif to evaluate the nature and age of their sources. During course of study we address the following questions: (1) is the North Patagonian Massif basement a single crustal block? (2) can distinct Lower to Upper Paleozoic magmatic pulses across the North Patagonian Massif be correlated? (3) is the Nd isotope signature of the North Patagonian Massif comparable to its neighbouring blocks, i.e. the Eastern Sierras Pampeanas (Pampia), Arequipa-Antofalla block, and other terranes?

The presented synthesis we present here serves in our opinion to gather new insight into the evolution of the continental crust in northern Patagonia and helps in testing published tectonic models.

2. Geological background

The North Patagonian Massif is located between 39° and 44°S and extends from the foothills of the Patagonian Andes to the Atlantic Ocean in southern Argentina (Fig. 1). Its northeastern boundary is covered by the thick sedimentary successions of the adjacent Colorado basin (Yrigoyen, 1999), while the southern border is located under the Meso-Cenozoic sedimentary

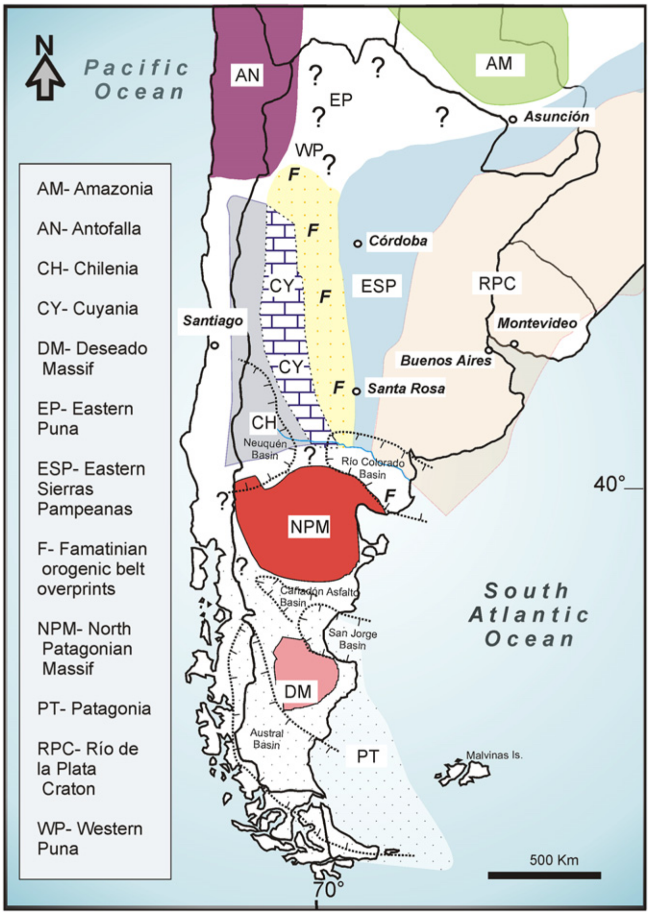

Fig. 1. Schematic distribution of the major crustal units of the margin of West Gondwana (modified after Rapalini, 2005 and Vaughan and Pankhurst, 2008 and references therein) using further information from Tohver et al. (2007) for the extension of the southern margin of the Río de la Plata craton. Pampia Terrane would be equivalent to the Eastern Sierras Pampeanas and Western Sierras Pampeanas according to Rapela et al. (2007).

successions of the San Jorge Basin. To the north it is bounded by the Rio de la Plata Craton (Dalla Salda et al., 1988), the Eastern Sierras Pampeanas (or Pampia terrane, Ramos, 1995), the Western Sierras Pampeanas (Rapela et al., 2007; Casquet et al., 2008), Cuyania (Ramos, 2004) and Chilenia (Ramos et al., 1986) terranes and to the south it is limited by the Deseado Massif (Fig. 1). Large volumes of granitic and metamorphic rocks of Lower Paleozoic to Mesozoic ages are present within the NPM that contain two Phanerozoic magmatic belts (Ramos, 2008): (a) a Northern Belt, with an E–W trend, that covers the regions of Sierra Grande-Valcheta and Chasicó-Mencué-La Esperanza and (b) a Western Belt with a NNW–SSE trend from Junín de los Andes to Gastre (Fig. 2). This last alignment of outcrops is postulated to cross into the Deseado Massif and continue into the submarine Dungenes Arch (Ramos, 2008).

In the Northern Belt more than 30 distinct plutons, sedimentary and metamorphic units are discontinuously exposed. In agreement with Pankhurst et al. (2006), the available geochronological dataset allows to define stages that involved crustal development: (1) Middle-Upper Cambrian sedimentation (530–500 Ma), (2) Lower Ordovician granitoid magmatism and metamorphism (485–470 Ma), (3) Upper Carboniferous-Lower Permian granitoid magmatism and deformation (∼300 Ma), (4) Early Permian mostly magmatically deformed calc-alkaline granitoid intrusions (290–270 Ma), Late Permian undeformed high-K calc-alkaline granitoids and volcanics (270 Ma) and Early Triassic highly evolved granitoids and rhyolitic magmatism (ca. 250 Ma).

In the Western Belt similarly different stages can be recognized using the crystallization age criteria: (1) Devonian tonalites and associated migmatites, (2) Early Carboniferous granitoid suite (330 Ma), (3) Late Carboniferous “S-type granites” (320–310 Ma), (4) Early Permian calc-alkaline deformed granites (290–270 Ma) and (5) Late Permian K-calc-alkaline granites (270–250 Ma).

2.1. Analytical techniques

Sm–Nd isotopic analyses were performed on seven representative samples by conventional isotope dilution technique. The samples were spiked with a suitable amount of ^{150}Nd–^{149}Sm spike solution prior to dissolution and dissolved using standard HF-HNO_3 acid attack. Ion chromatographic procedures included a standard cation exchange column for preparation of a REE separate. REE separation was achieved using reversed ion chromatographic procedures (Richard et al., 1976). Measurements were performed on a TIMS Finnigan Triton at the GZG – Department of Isotope Geology (Georg August Universität Göttingen, Germany). Total procedure blanks were consistently below 150 pg for Sm and Nd. Mass fractionation was corrected exponentially using a ^{146}Nd/^{144}Nd ratio of 0.7219. ^{143}Nd/^{144}Nd and ^{145}Nd/^{144}Nd values ($n = 5$) for a Nd inhouse solution during course of study were 0.511797 ± 32 and 0.348392 ± 18, respectively. This ^{143}Nd/^{144}Nd ratio corresponds to a value of 0.511837 of La Jolla standard solution. The ^{149}Sm/^{152}Sm value of a Sm inhouse solution ($n = 5$) is 0.516869 ± 42.

3. Summary of the magmatic and metamorphic events in the North Patagonian Massif

3.1. Northern magmatic belt

3.1.1. Cambrian sedimentation (530–500 Ma)

Metaclastic rocks are represented by isolated septas of low grade pelitic schists, metasandstones, together with marbles and limestones known as El Jagüelito Formation in the Sierra Grande locality, Nahuel Niyeu Formation in Yaminué -Valcheta and Colo-Niyeu Formation in La Esperanza area (Figs. 2 and 3).

In the Sierra Grande locality, west of Puesto El Jaguelito, El Jagüelito Formation is made up by a sequence of quartzitic phyllites, metawackes with calcitic schist and amphibolites lenses intruded by the Permian Piedras Blancas pluton (Giacosa, 1997). In the southern part, near Arroyo Salado, the sequence is composed of interbedded metapelites, metapsammites and metaquartzites and intruded by undeformed Ordovician granitoids like the Arroyo Salado and Playas Doradas plutons (Varela et al., 2009; Pankhurst et al., 2006 and references therein).

In the Valcheta-area the low-grade meta-sedimentary rocks known as Nahuel Niyeu Formation (Chernicoff and Caminos, 1996) consist of greywackes, siltstones, shales and scarce hornfels. The Nahuel Niyeu metasediments are intruded by undeformed Ordovician granitoids (Caminos, 2001; López de Luchi et al., 2008). The Nahuel Niyeu Formation is additionally constrained through unconformably overlaying marine sedimentary rocks of the Sierra Grande Formation of Late Silurian to Early Devonian age.

In the La Esperanza area (Fig. 2), Labudía and Bjerg (1994) described slates, phyllites and siltstones of an uncertain age, intruded by the undeformed Prieto Granodiorite (Llambías and Rapela, 1984). In the nearby El Cuy locality, Saini-Eidukat et al. (1999) mentioned very low grade metamorphic rocks intruded by foliated granitoids.

Cambrian sedimentation in the Valcheta and Sierra Grande areas is constrained by detrital zircons ages of Nahuel Niyeu (515 Ma) and El Jagüelito (535 Ma) formations (Pankhurst et al.,

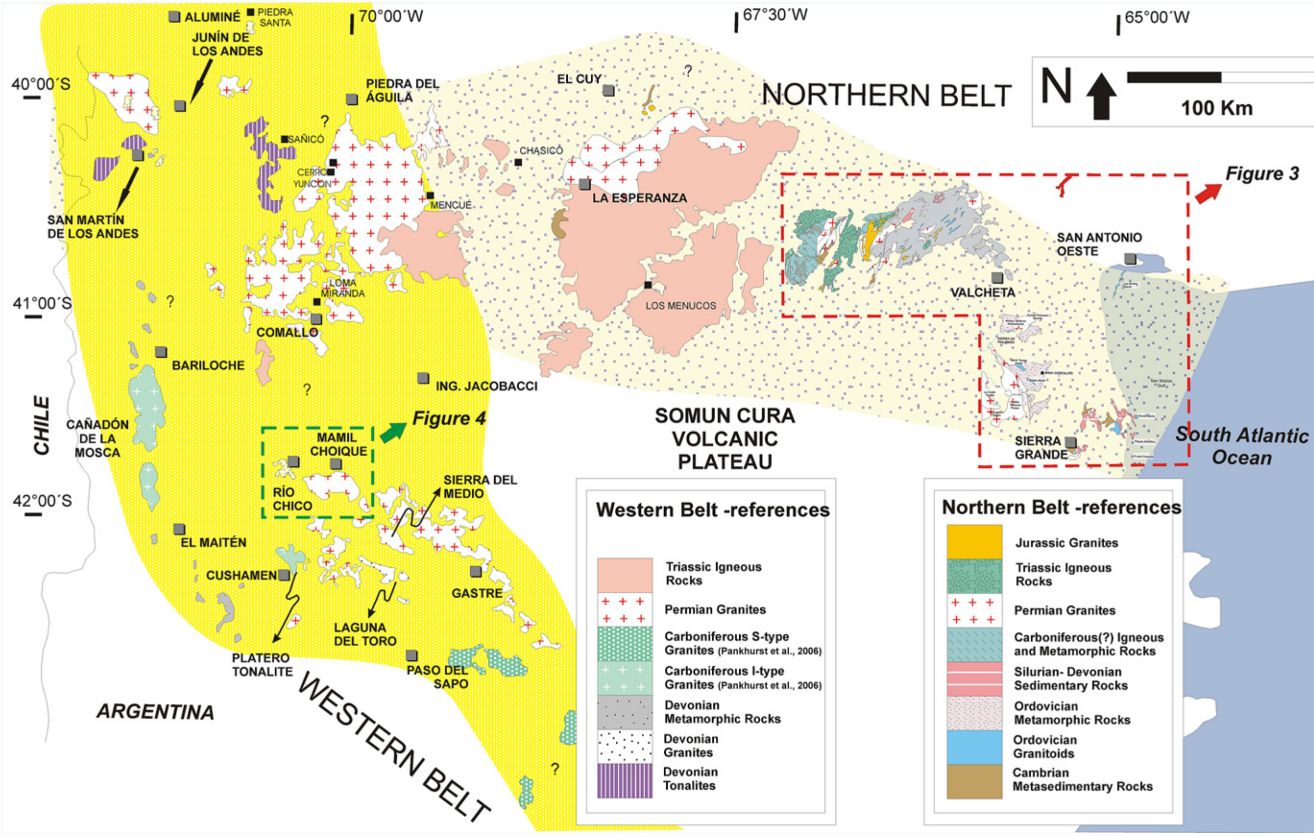

Fig. 2. Sketch map of the North Patagonian Massif, showing the Pre-Cretacic geology (excluding the volcanic rocks from the Marifil Formation) and the main referred localities.

2006) and by preserved ichnofauna in El Jagüelito Formation (González et al., 2002).

3.1.2. *Lower Ordovician granitic magmatism and metamorphism (470–475 Ma)*

Metamorphic rocks of the Sierra Grande area relate to the Mina Gonzalito Complex and have been described as biotite-muscovite-garnet schists with amphibolite lenses, gneisses, amphibolites, concordant foliated granitoids (La Tapera and Santa Teresa stocks), dolomites, crystalline limestones and injected schist in the south and west (Giacosa, 1997). Recently, González et al. (2008b) divided the unit into two fringes separated by a NNW–SSE ductile shear zone. The western fringe is presumably affected by igneous activity and higher metamorphic conditions than the eastern fringe, which also hosts a Pb–Zn mineralization zone. The latter is considered as a deeper equivalent to El Jagüelito Formation based on available isotope data indicating a metamorphic event between 472 Ma and 469 Ma (Pankhurst et al., 2001) and a maximum deposition age between 515 Ma and 535 Ma (Pankhurst et al., 2006).

Ordovician granitic magmatism in the Sierra Grande area is represented by the undeformed Arroyo Salado (formerly known as Monocchio), Sierra Grande and the Playas Doradas (also named as Punta Bahía) granites that are nicely constrained by WR Rb–Sr and zircon U–Pb dating to an age of 475 Ma (Varela et al., 2009; Pankhurst et al., 2006). The Arroyo Salado and Playas Doradas plutons are dominantly of granodioritic, subordinated tonalitic composition mainly build up of plagioclase, quartz, K-feldspar, biotite and variable amounts of amphibole. Opaque minerals and apatite are common accessories. Microgranular and metamorphic enclaves of El Jagüelito Formation are observed. The Sierra Grande pluton is a biotite rich-granite. The Arroyo Salado Pluton led to a contact metamorphic overprint of the El Jagüelito Formation host that were previously regionally overprinted, as already proposed by Giacosa and Paredes (2001). In the Valcheta area, muscovite monzogranites were recently dated as late Ordovician by López de Luchi et al. (2008) and Tohver et al. (2008). These ages were confirmed by 470 ± 2 Ma Ar–Ar dating on muscovite data provided by Gozálvez (2009) on the same pluton. These rocks lack any penetrative fabric. They are composed of subhedral acid oligoclase and anhedral, partially pertithic, microcline, which develop myrmekites in contact with each other. Anhedral quartz exhibits parallel to incipient chessboard microtextures.

Late Silurian to Devonian Sierra Grande Formation marine sedimentary rocks unconformably overly older formations. Inheritance patterns exhibit supplies from rocks of 480 Ma, 523 Ma, 608 Ma and ~1000 Ma, these three last peaks coherent with those found in the Nahuel Niyeu Formation, El Jagüelito Formation and Mina Gonzalito Complex (Pankhurst et al., 2006; Uriz et al., 2008).

3.1.3. *Carboniferous (?)–Permian (~300 Ma) granitoid emplacement and deformation*

The Yaminué Complex, originally defined by Caminos and Llambías (1984), comprises strongly foliated granitoids, apparently emplaced in gneisses, schists and marbles of unknown age. Nahuel Niyeu Formation and Yaminué Complex are in contact to the south of Nahuel Niyeu village (von Gosen, 2003). For many years this unit was considered Precambrian (Caminos et al., 1994), but more recently, Basei et al. (2002) suggested a Late Carboniferous or Permian age for this complex based on conventional U–Pb zircon dating. High temperature solid-state deformed foliated granitoids gave ages of 281 ± 29 and 276 ± 11 Ma in the southern part and of 305 ± 31 Ma in the central sector whereas an age of 244 ± 14 Ma is shown for a granitoid that exhibits a greenschists facies deformation that may imply episodes of lead loss.

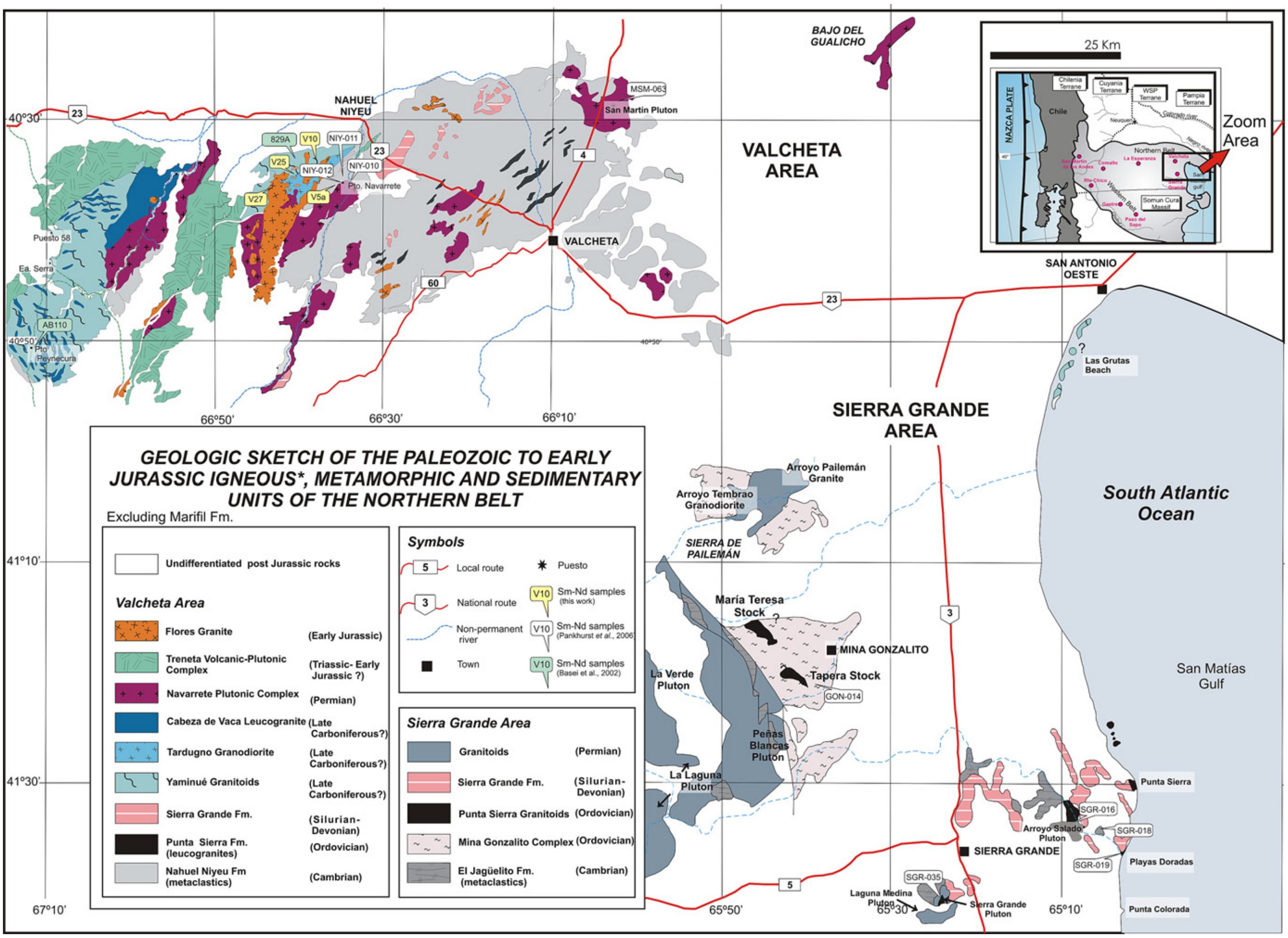

Fig. 3. Geologic sketch of the main Early Palezoic to Jurassic unit in the NE of the North Patagonian Massif. Based on Rapalini et al. (2010). Sampling sites are indicated in rectangles.

The Tardugno Granodiorite is exposed to the south of the Nahuel Niyeu village (Fig. 3) and shows a deformed porphyritic fabric variably affected by a heterogeneously developed foliation that led to S–C surfaces (Chernicoff and Caminos, 1996). Tardugno Granodiorite is intruded by tonalitic melts of the Permian Navarrete Plutonic Complex and in contact with the Nahuel Niyeu Formation along steeply dipping NE trending mylonitic shear zones.

Along the Atlantic shore, south of San Antonio Oeste (Fig. 2) González et al. (2008a) describe the Las Grutas igneous-metamorphic Complex as folded granodioritic orthogneisses with scarce schist septas associated with a deformed leucogranite known as Piedras Coloradas. They relate to each other by an ENE–WSW low-angle thrust dipping 20° towards the NNW. Petrographical descriptions and structural data suggest an evolution similar to the Permian thrust-tectonics described by von Gosen (2002) and López de Luchi et al. (2010) in the Valcheta area.

3.1.4. *Lower Permian calc-alkaline granitoids (290–280 Ma) and Upper Permian undeformed high-K calc-alkaline granitoids (~260 Ma)*

The Navarrete Plutonic Complex is the most extended granitic unit in the Valcheta area (Figs. 2 and 3), and is mainly composed of granodiorites, tonalites and granites dominated by magmatic and submagmatic microstructures that – on the basis of major and some trace-element data – was assigned to a subduction regime (Rapela and Caminos, 1987). In several areas the Navarrete Plutonic Complex is cut by early Jurassic epizonal granites or covered by younger, volcanic rocks. However, where the Navarrete Plutonic Complex is intruding the Yaminué Complex, contacts are sharp at the meter scale, but more irregular and transitional at a finer scale. Pankhurst et al. (2006) obtained a U/Pb SHRIMP zircon age of 281 ± 3 Ma for a biotite granodiorite at Puesto Navarrete (Fig. 3). These authors suggested an Early Permian age for the entire Navarrete Plutonic Complex. In the La Esperanza area (Fig. 2), U–Pb zircon SHRIMP dating on granites and associated volcanic rocks suggested an interval between 273 and 246 Ma for the magmatism (Pankhurst et al., 2006). The Prieto Granodiorite (273 ± 2 Ma), the largest and oldest unit, intrudes a sequence of low grade metasedimentary rocks. East of Estancia La Esperanza, the Prieto Granodiorite is intruded by the 264 Ma Collinao felsitic dome (Llambías and Rapela, 1984; Pankhurst et al., 2006). Shortly after the acid volcanism of the Dos Lomas Complex, represented by the undeformed leucocratic Calvo Granite (250 Ma U–Pb SHRIMP in zircon, Pankhurst et al., 2006) was emplaced. Undeformed Permian magmatic unit would extend up to the southeastern North Patagonian Massif (Pankhurst et al., 2006).

3.1.5. *Lower Jurassic highly evolved granitoids and rhyolitic magmatism (~190 Ma)*

Near Valcheta, an erosional unconformity separates the Navarrete Plutonic Complex from the Treneta Plutonic-Volcanic Complex which is represented by Triassic (?) andesites, rhyolitic tuffs and dacitic ignimbrites. The Early Jurassic Flores Granite (Rb/Sr isochron age of 188 ± 3 Ma, Pankhurst et al. 1993; muscovite K–Ar cooling ages of 188 ± 2 and 193 ± 5 Ma, López de Luchi et al., 2008) intrudes the Navarrete Plutonic Complex (Fig. 3). This is the last known stage of the plutonic activity exposed in the region.

3.2. Western Belt

3.2.1. Devonian granitoids and associated migmatites with metamorphic septas

The igneous and metamorphic basement of the northern Patagonian Cordillera between the cities of Aluminé and San Martín de los Andes (Fig. 2) is often described as a suite of migmatites, schists and low grade metamorphic rocks as siltstones and phyllites interbedded with amphibolitic and dioritic lenses as well as granitoids. Turner (1973) classified them as ectinites and "mixed rocks" and named them as Colohuincul Formation. Dalla Salda et al. (1991) characterized the basement in the San Martín de los Andes area as paragneisses bearing sillimanite and biotite, quartzitic schists and tonalitic and granodioritic migmatites and named them as the Colohuincul Complex. These authors also separated the deformed San Martin de los Andes Tonalite and the Lago Lacar Granodiorite from the Permian Huechulafquen granodiorites (WR Rb–Sr Isochron, Varela et al., 1994). San Martín de los Andes Tonalite includes two varieties, one biotite rich and another biotite-hornblende rich. There is a single K–Ar biotite-cooling age of 376 ± 9 Ma for Lago Lacar Granodiorite (Dalla Salda et al., 1991), whereas the age of the San Martín de los Andes Tonalite (393 ± 3 Ma U–Pb in zircon) was recently determined by Godoy et al. (2008) in a tonalitic gneiss exposed in the southern shore of the Lacar Lake at San Martín de los Andes. Near San Martin de los Andes town (Fig. 2) a migmatite yielded a WR Rb–Sr age of 368 ± 9 Ma (Lucassen et al., 2004) whereas Varela et al. (2005) presented a 375 ± 12 Ma K–Ar biotite-cooling age for migmatites located near Junín de los Andes. These ages of ca. 380 Ma could be interpreted as representative of the metamorphic peak according to Lucassen et al. (2004). Ages on San Martín de los Andes Tonalite and equivalents could also be slightly older than the ~400 Ma thermal event as proven by a 401 ± 3 Ma U–Pb SHRIMP age (Pankhurst et al., 2006), 419 ± 27 Ma in the city of San Martin de los Andes and 390 ± 5 Ma across the road in the Cerro Curruhuinca (Varela et al., 2005).

It is unclear whether or not the Colohuincul Complex and associated tonalites would extend farther east. Near Sañicó, orthogneisses and metadiorites yielded an age of 425 ± 28 Ma (U–Pb) while leucogranites are of 387 ± 5 Ma. In addition, an U–Pb zircon age of 348 ± 11 Ma for the Collon Cura granite has been recently published (Varela et al., 2005). Further north, near Aluminé city (Fig. 2), the basement comprises medium-grade gneisses, amphibolites/diorites and migmatites invaded by granites associated to local mylonitic zones. West to the city of Aluminé, Franzese (1995) described the Piedra Santa Complex, a series of low grade greenschist metamorphic rocks with WR K/Ar ages of 311 ± 16 Ma and 372 ± 18 Ma.

Southwest Sañicó, Varela et al. (1991) described weakly foliated biotite- and biotite-hornblende tonalites and obtained K/Ar cooling ages in biotite and biotite + amphibole between 350 and 320 Ma, suggesting that some of these rocks are comparable to the Devonian tonalites in San Martin de los Andes.

In the southwestern sector of the North Patagonian Massif the older unit is the Cushamen Formation, which has been described in Rio Chico (Río Negro Province) by Cerredo (1997) (Fig. 4) as a low-greenschist to upper amphibolite facies metasedimentary series composed of metapelites, metapsammites with scarce interlayed metavolcanic rocks, leucogranitoids and pegmatite veins. Inherited zircons sampled from the Cushamen Formation type locality along the Río Chico (Chubut Province) would indicate a maximum age of deposition of 330 Ma (Hervé et al., 2005).

West of Gastre, near Laguna del Toro at Puesto Viuda de Cáceres (Fig. 2), Pankhurst et al. (2006) obtained a 371 ± 2 Ma (U–Pb) crystallization age in a megacrystic granite, which partially confirms the poorly fitted WR Rb–Sr isochron of 345 ± 35 Ma (Rapela et al., 1992) in a "biotite granite-gneiss". Proserpio (1978) described this rock as an orthogneiss that according to Cerredo (pers. communication) is interlayered with the Cushamen Formation.

The southernmost extension of the Devonian belt presumably is represented by the Colan-Cohuen (locality not included in Fig. 2) megacrystic granite as suggested by Pankhurst et al. (2006), based on lithological affinities and a 394 ± 4 Ma age (zircon U–Pb).

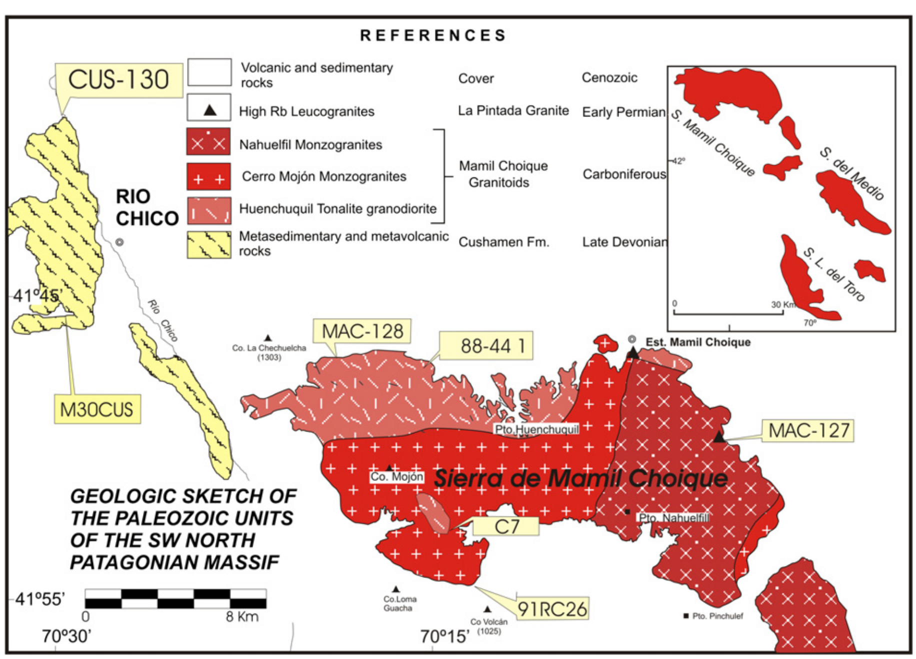

Fig. 4. Geologic sketch of the Paleozoic units in the southwestern corner of the North Patagonian Massif. Sampling sites are indicated in yellow rectangles.

3.2.2. Medium grade-metamorphism (~380 Ma) and Lower Carboniferous granitoid suite (330 Ma)

The existence of a continuous 120 km N–S belt of Early Carboniferous (~330 Ma – U–Pb zircon ages) metaluminous I-type gabbros-amphibolites and diorites along the Cordón del Serrucho, between San Carlos de Bariloche and El Maitén (Fig. 2) has been supported by recent geochemical and geochronological (U–Pb in zircons) data (Varela et al., 2005; Pankhurst et al., 2006). The former authors extended this belt abruptly 80 km to the southeast at 41°50′S up to an isolated outcrop of a foliated tonalite included in the El Platero Tonalite (Volkheimer and Lage, 1981). In between, in El Maitén and Rio Chico areas, the most conspicuous outcrops of the metaclastic Cushamen Formation are exposed. The age of metamorphism of Cushamen Formation is still poorly constrained. Pankhurst et al. (2006) agreed with a metamorphic event at ca.330 Ma based on detrital zircon ages from a biotite gneiss in El Maitén. For the Río Chico area, Hervé et al. (2005) reported a small metamorphic peak at 325 Ma, that follows more important ones around 450, 425 and 380 Ma. Field evidence indicates that the Platero Tonalite (329 ± 4 Ma, Pankhurst et al., 2006) intrudes at its type locality an already metamorphosed Cushamen Formation host.

3.2.3. Upper Carboniferous granites (320–310 Ma)

Pankhurst et al. (2006) obtained precise crystallization ages (U–Pb in zircons) of 314 ± 2 and 318 ± 2 Ma in Paso del Sapo and in Sierra de Pichiñanes granites, respectively; but few references on these Paleozoic granites are available.

3.2.4. Permian deformed and undeformed granites of the Sierra de Mamil Choique and equivalents

The Mamil Choique Granitoid suite (*sensu* López de Luchi and Cerredo, 1997, 2008) extends along the western margin of the North Patagonian Massif from Sañico to the Laguna del Toro area. Its type locality, Sierra de Mamil Choique, consists of three peraluminous calc-alkaline units: the banded Huenchuquil tonalites and granodiorites and the Cerro Mojón biotite-muscovite monzogranites which are intruded by the Nahuelfil monzogranites. Recent geochronologic studies point towards a zircon crystallization age of 272 Ma U–Pb (Varela et al., 2005) for Huenchuquil tonalites-granodiorites and K–Ar muscovite cooling ages of approximately 265–230 Ma (López de Luchi et al., 2006). In the northeast of the Sierra de Mamil Choique small stocks and dikes of an undeformed leucomonzogranite known as La Pintada granite are exposed. This low-Sr garnet lepidolite leucomonzogranite yielded a WR Rb/Sr isochron of 278 ± 8 Ma (López de Luchi et al., 2000).

The migmatic rocks of the Sierra del Medio crop out to the northwest of the Gastre area. Llambías et al. (1984) considered the Sierra as composed of granitic migmatites and equigranular granites with minor development of porphyritic textures and hence, assigned it to the Mamil Choique Formation. They also mentioned small septas of biotite-sillimanite and amphibolic schists (Cushamen Formation) within the migmatites. Rapela et al. (1992) obtained a WR Rb–Sr isochron of 267 ± 27 Ma in a two-mica granodiorite of the Sierra del Medio but argued for a rehomogenisation during a metamorphic event. Nevertheless, this age could also represent a resetting during the voluminous Mamil Choique Granitoids thermal episode.

4. New Sm–Nd data and description of our samples

During course of this study Sm–Nd isotope systematics of seven key samples in the Northern (Valcheta) – and the Western (Río Chico-Mamil Choique) Belt (Table 1) were analysed.

In Valcheta a metasedimentary rock of the Nahuel Niyeu Formation (sample V5a) was chosen. It was sampled from fine grained schists in which a continuous schistosity is defined by chlorite-muscovite-quartz and plagioclase. Thin quartz veins are parallel to the main fabric. Locally quartz aggregates exhibit triple junctions.

Samples V25 and V10 belong to the Yaminué Complex. V25 corresponds to a grey biotite-hornblende granodiorite comprising plagioclase (45–55%), quartz (25–30%), around 20% mafic minerals – mainly biotite and scarce hornblende – as well as accessory magnetite, titanite, zircon, apatite and allanite. Chlorite, epidote and sericite are considered as secondary minerals. The sample exhibits a weak magmatic fabric defined by the alignment of plagioclase crystals. A non-penetrative high temperature subsolidus deformation is preserved in the chessboard pattern of quartz. Textures vary from dominant coarse grained and equigranular to slightly porphyritic. In the latter, up to 6 mm subhedral plagioclase is included in a matrix in which finer grained subhedral to anhedral plagioclase is separated by quartz and biotite hornblende intergrowth. Plagioclase (An_{23-43}) is mostly fresh and usually zoned. Zonation is complex, mostly oscillatory and consists of corroded calcic cores surrounded by normally zoned limpid rims. V10 was collected from the Tardugno Granodiorite and it is a porphyritic biotite-granodiorite orthogneiss with perthitic K-feldspar megacrysts, partially converted into microcline. The granodiorite is intruded by tonalite melts of the Navarrete Plutonic Complex and is in contact with the Nahuel Niyeu Formation along steeply dipping NE trending mylonitic shear zones. The dominant fabric is of S-C type with a WNW–ESE trend and NE dip of up to 40°. K-feldspar porphyroclasts exhibit rather coarse core-mantle structures and contain flame perthites. Myrmekites are scarce. Locally porphyroclasts are polygonised entirely with well-developed triple points. Narrow shear zones with intense grain-size reduction cut the core-mantle fabric of the feldspars. Bands of epidote and chlorite wrap around some polygonised augen. Biotite (partly chloritised), chlorite and dynamically recrystallized quartz define the S–C fabric. Kinked and bent muscovite occurs locally. Large quartz grains show elongate subgrains and contain bands that are recrystallized dynamically. Coexisting feldspar recrystallization and quartz texture suggest temperatures of 400–500 °C (Passchier and Trouw, 2005), whereas the dynamically recrystallized finer grained shear bands and the chlorite indicate somewhat lower temperatures compared with those of the more penetrative pattern.

Table 1
New Nd isotope data for the North Patagonian Massif localities are shown in Figs. 3 and 4.

Unit	Sample	Lithology	Location	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	T_{DM} (Ga)	$f_{Sm/Nd}$	ε_{Nd} (t)
Nahuel Niyeu Fm.	V5a	Metasedimentary rock	40°35′39″S 66°34′12″W	6.10	29.72	0.1241	0.512141	1.713	−0.37	−5.07
Yaminué Complex	V25	Deformed Tonalite	40°36′25″S 66°40′10″W	6.17	33.53	0.1113	0.512153	1.482	−0.43	−6.40
Yaminué Complex	V10	Orthogneiss	40°35′31″S 66°37′26″W	6.00	27.85	0.1302	0.512256	1.629	−0.34	−4.91
Flores Granite	V27	Granite	40°35′39″S 66°34′12″W	3.64	25.62	0.0858	0.512230	1.400	−0.56	−5.34
Cushamen Fm.	M30Cus	Metaclastic rock	41°45′15″S 70°29′26″W	4.69	24.87	0.1140	0.512076	1.638	−0.42	−7.48
Mamil Choique Granitoids	88-441	Granodiorite	41°46′86″S 70°16′18″W	5.36	28.66	0.1131	0.512281	1.310	−0.43	−3.97
Mamil Choique Granitoids	c7	Monzogranite	41°51′53″S 70°14′26″W	3.28	18.24	0.1088	0.512227	1.340	−0.44	−4.87

Table 2
Recalculated Nd isotopic data for North Patagonian Massif.

Suites and rock types			Age (Ma)		Sample		T_{DM} (Ga)[a]	$f_{Sm/Nd}$[b]	ε_{Nd} (t)[b]
Lower Cambrian–Upper Ordovician (470–550 Ma)									
Sedimentation in Precambrian(?) – Cambrian Basin									
El Jaguelito Fm	Metasandstone	U–Pb Inh	530	P	SGR-018	P	1.558	–0.38	–3.70
Nahuel Niyeu Fm	Metasedimentary				V5a	N	1.713	–0.37	–5.07
Nahuel Niyeu Fm	Metapelite	U–Pb Inh	515	P	NIY-012	P	1.671	–0.40	–5.37
Post metamorphic and Massive Melting – granitic intrusion									
Sierra Grande									
Arroyo Salado	Granite	U–Pb	475 ± 6	P	SGR-016	P	1.573	–0.34	–3.00
Sierra Grande	Granite	U–Pb	476 ± 6	P	SGR-019	P	1.453	–0.38	–2.63
Playas doradas	Granite	U–Pb	476 ± 4	P	SGR-035	P	1.480	–0.38	–2.88
Mina Gonzalito Complex	Bt-Grt Gneiss	U–Pb	472 ± 5	O	GON-014	P	1.648	–0.37	–4.80
Eastern Río Colorado									
Río Colorado	Granodiorite	U–Pb	474 ± 6	P	PIM-113	P	1.736	–0.34	–4.66
Curacó	Granite	U–Pb	475 ± 5	P	PIM-115	P	1.633	–0.24	–5.32
Devonian Closure of the Sierra Grande sea – deformation									
Carboniferous–Permian Extended Magmatism									
Metamorphism/syn-deformational Granitic Intrusion									
Valcheta									
Yaminué Complex	Ortogneiss				V10	N	1.629	–0.34	–4.91
Yaminué Complex	Foliated granodiorite	U–Pb	~300	B	AB110	B	1.534	–0.53	–5.80
Yaminué Complex	Foliated granodiorite				829A	B	1.497	–0.34	–3.59
Yaminué Complex	Tonalite				V25	N	1.482	–0.43	–6.40
Extended Late Permian Magmatism Stage II: post-deformational granitoids									
Post deformational Granitic Intrusion									
Calc-alkaline Magmatism									
Valcheta									
Navarrete	Granodiorite	U–Pb	282 ± 3	P	NIY-010	P	1.292	–0.36	–2.08
Navarrete (?)	Quartz porphyry				NIY-011	P	1.413	–0.34	–2.93
La Esperanza									
Prieto	Granodiorite	U–Pb	273 ± 2	P	LES-119	P	1.365	–0.43	–4.95
Donosa	Granite	Rb–Sr WR	259 ± 16	T	LES-120	P	1.614	–0.48	–9.82
High-K calc-alkaline Magmatism									
Valcheta									
San Martin	Granodiorite	U–Pb	~267	P	MSM-063	P	1.486	–0.39	–5.38
La Esperanza									
Dos Lomas	Rhyolite dome	U–Pb	264 ± 2	P	LES-125	P	1.304	–0.50	–6.14
Calvo	Granite	U–Pb	250 ± 2	P	LES-118	P	1.640	–0.51	–7.68
Early-Mid Jurassic Gondwana break up igneous rocks									
Valcheta									
Flores	Granite	Rb–Sr WR	188 ± 3	Q	V27	N	1.400	–0.56	–5.34
Sierra Grande									
El Sotano	Deformed granodiorite	U–Pb	185	S	LGZ-3	S	1.432	–0.53	–5.71
Upper Silurian–Upper Devonian Colohuincul Basin – North Limay river (?–360 Ma)									
Syn-Deformational Metamorphism and Migmatization									
Sañicó Area									
Sañicó orthogneiss	Orthogneiss Enclave	U–Pb	425 ± 28	V	AB165B	V	2.102	–0.38	–7.00
Sañicó orthogneiss	Orthogneiss	U–Pb	425 ± 28	V	AB165A	V	1.744	–0.32	–9.30
San Martin de Andes Area									
Colohuincul Complex	Gneiss				LCU-251	P	1.547	–0.42	–5.53
Colohuincul Complex	Migmatite	K–Ar (bt)	375 ± 12	V	AB157A	V	1.415	–0.49	–5.70
Colohuincul Complex	Tonalite enclave				SAN-248	P	1.632	–0.35	–4.57
SMA Tonalite	Tonalite	U–Pb	419 ± 27	V	AB152	V	1.464	–0.37	–3.24
SMA Tonalite	Granite	U–Pb	395 ± 4	P	LOL-250	P	1.339	–0.37	–1.70
SMA Tonalite	Tonalite	U–Pb	390 ± 5	P	AB154	V	1.429	–0.42	–4.16
SMA Tonalite	Tonalite				88CC-4D	D	1.480	–0.39	–3.53
SMA Tonalite	Gneiss				87CC3-F	D	1.471	–0.37	–3.30
SMA Granodiorite Lacar	Granodiorite				AB13	V	1.558	–0.37	–4.39
Gastre Area									
Cáceres Granite	Granite	U–Pb	371 ± 2	P	GAS-027	P	1.760	–0.32	–5.02
Lower Carboniferous Cushamen Basin – South Limay River (?–330 Ma)									
Borderline Serrucho Magmatic arc and metamorphism of the Cushamen back arc basin									
Cordón del Serrucho									
	Granodiorite	U–Pb	330 ± 4	P	SER-044	P	1.133	–0.31	1.20
	Tonalite	U–Pb	329 ± 4	P	PLA-049	P	1.059	–0.26	2.80
	Amphibolite*	U–Pb	323 + 3	P	MOS-043	V	1.072	–0.19	0.14
	Amphibolite	U–Pb	321 ± 2	V	AB123	V	1.618	–0.21	–0.58

(*continued on next page*)

Table 2 (*continued*).

Suites and rock types			Age (Ma)		Sample		T_{DM} (Ga)[a]	$f_{Sm/Nd}$[b]	ε_{Nd} (t)[b]
Cordón del Maitén									
Cushamen Formation	Gneiss	U–Pb Inh	330	P	MAI-047	P	1.619	−0.41	−6.92
Río Chico Area									
Cushamen Formation	Metaclastite	K–Ar (Ms)	263 ± 3	M	M30	N	1.638	−0.42	−7.48
Isolated Upper Carboniferous–Lower Permian Magmatism (∼300)									
Paso del Sapo-Sierra de Pichiñanes									
	Bt-Grt granite		318 ± 2	P	PIC-216	P	1.479	−0.16	−5.03
	Mylonitised granite				SAP-209	P	1.496	−0.52	−5.20
	Foliated Bt-Hnb granodiorite		314 ± 2	P	SAP-210	P	1.564	−0.38	−5.46
	Granite				PIC-213	P	1.380	−0.48	−6.22
Extended Early Permian Magmatism – Stage I: syn-deformational granitoids									
Mamil Choique Sierra									
Tunnel Tonalite	Tonalite	U–Pb	295 ± 2	P	CUS-130	P	1.338	−0.46	−5.22
Gastre									
	Bt Granodiorite	U–Pb	294 ± 3	P	GAS-025	P	1.251	−0.45	−3.62
	Bt Granite-gneiss				GAS-48	R	1.481	−0.39	−4.97
Sierra del Medio									
	2mica granodiorite gneiss	Rb–Sr WR	269 ± 27	R	GAS25	R	1.763	−0.31	−5.43
	2mica granodiorite gneiss				GAS32	R	1.457	−0.41	−5.09
Mamil Choique Sierra									
MCG Huenchunquil facies	Granodiorite	K–Ar (Bt)	262 ± 3	M	88-44-1	N	1.310	−0.43	−3.97
MCG Huenchunquil facies	Foliated granodiorite	U–Pb	281 ± 2	P	MAC-128	P	1.300	−0.45	−4.48
MCG Cerro Mojon Facies	Monzogranite				C7	N	1.340	−0.44	−4.87
?	Tonalite?				91RC26	P	1.530	−0.31	−3.23
Comallo Area									
	Deformed Tonalite	U–Pb	281 ± 17	P	AB27C	U	1.457	−0.43	−7.02
	Foliated tonalite	U–Pb	269 ± 13	U	AB 120	U	1.312	−0.47	−4.98
Extended Late Permian Magmatism Stage II: post-deformational granitoids									
Mamil Choique Sierra									
MCG La Pintada	Leucogranite	Rb–Sr WR	278 ± 8	L	MAC-127	P	1.414	−0.37	−3.80

References: B – Basei et al. (2002); D – Dalla Salda et al. (1991); L – López de Luchi et al. (2000); M – López de Luchi et al. (2005); N – This paper; O – Pankhurst et al. (2001); P – Pankhurst et al. (2006); Q – Pankhurst et al. (1993); R – Rapela et al. (1992); S – Sato et al. (2004); T – Pankhurst et al. (1992); U – Varela et al. (1999); and V – Varela et al. (2005).

[a] T_{DM1}'s equation proposed by Goldstein et al. (1984): $T_{DM1} = 1/\lambda \ln \{1 + [(^{147}Sm/^{144}Nd)s - 0.51315]/[(^{147}Sm/^{144}Nd)s] - 0.2137$considering parameters used by Wu et al. (2003). T_{DM2}, using the assumptions proposed by Keto and Jacobsen (1987), is calculated as: $T_{DM2} = T_{DM1} - (T_{DM1} - t) \times [(fcc - fs)/(fcc - fdm)]$ Where t is the age of intrusion, and fcc, fs and fdm are $f_{Sm/Nd}$ values of the continental crust, sample and depleted mantle, respectively and as used by Wu et al. (2003). The use of single stage model is restricted to $-0.3 \geq f_{Sm/Nd} \geq -0.5$, within the values of the $T_{DM1} \approx T_{DM2}$, and to the two stage model if $-0.3 \leq f_{Sm/Nd}$ or $f_{Sm/Nd} \leq -0.5$.

[b] $f_{Sm/Nd} = [(^{147}Sm/^{144}Nd)s/(^{147}Sm/^{144}Nd)CHUR] - 1$; $\varepsilon_{Nd}(t) = [(^{143}Nd/^{144}Nd)s/(^{143}Nd/^{144}Nd)CHUR - 1] \times 10{,}000$ where $(^{143}Nd/^{144}Nd)$sand $(^{147}Sm/^{144}Nd)$s are the measured parameters $(^{143}Nd/^{144}Nd)CHUR = 0.512638$ and $(^{147}Sm/^{144}Nd)CHUR = 0.1967$.

Sample V27 corresponds to the Early Jurassic Flores granite. It is a medium to coarse grained, pink to reddish porphyritic granite composed of 30–50% of highly perthitic orthoclase, 10–25% of albite-oligoclase, 30–50% of quartz and up to 5% of reddish brown to green biotite and opaque minerals. Quartz and sometime K-feldspar develop megacrysts. Biotite and plagioclase grains are commonly but not universally altered. Biotites have narrow rims of secondary white mica and the cores of some plagioclase grains have been sericitized to varying degrees.

In the Río Chico area, medium grade gneisses of the Cushamen Formation (sample M30) were collected near to a discontinuous belt of D3 shear zones (Cerredo, 1997). This sample corresponds to a medium-grade schist that belongs to the biotite-garnet zone (Cerredo, 1997).

Samples C7 and 88-44 were obtained, respectively, from the Cerro Mojón and Huenchuquil facies of the Mamil Choique granitoids, exposed in the SW and NW parts of the Sierra de Mamil Choique.

C7 corresponds to an equigranular medium grained biotite-muscovite monzogranite composed of microcline, plagioclase (An_{13-25}), quartz, biotite and muscovite as well as accessory apatite and zircon. Small relict magmatic epidote with allanite cores and large skeletal epidote inclusions within plagioclase and biotite are present. Parallel alignment of subhedral unzoned plagioclase and some microcline crystals could be considered as a primary magmatic feature. Myrmekites are abundant together with leucocratic K-feldspar-quartz-albite aggregates filling interstices. The latter could be interpreted as late crystallization residua. Plagioclase is subhedral, with poorly defined zonality.

Sample 88-44 is a biotite-hornblende granodiorite with primary magmatic structures. Plagioclase is calcic oligoclase, biotite is green and microcline is generally abundant. Amphibole appears as individual crystals with wormy and resorbed boundaries against plagioclase, epidote, biotite and later minerals; and magmatic sphene appears as large euhedral crystals (up to 3.5 mm) bearing some opaque minerals cores; which is an early crystallizing phase as it is found sometimes as inclusions. Opaque minerals, mainly magnetite, appear as subhedral crystals forming the rock aggregate or as inclusions in later crystallizing phases. Apatite is present.

5. Nd isotopic signatures of different groups of rocks

We compiled previous Sm–Nd isotopic data from Dalla Salda et al. (1991), Rapela et al. (1992), Basei et al. (2002), Sato et al. (2004), Varela et al. (2005) and Pankhurst et al. (2006). T_{DM} (Nd) model ages are presented in Table 2 together with $f_{Sm/Nd}$ and initial ε_{Nd} values (Fig. 5).

5.1. Isotopic evolution of the Northern Belt during the Paleozoic

The low-grade metasedimentary units, El Jagüelito Formation and Nahuel Niyeu Formation, show old T_{DM} (Nd) ages (1.72–1.55 Ga), negative ε_{Nd} (t) values (−5 to −4); and in all cases typical crustal

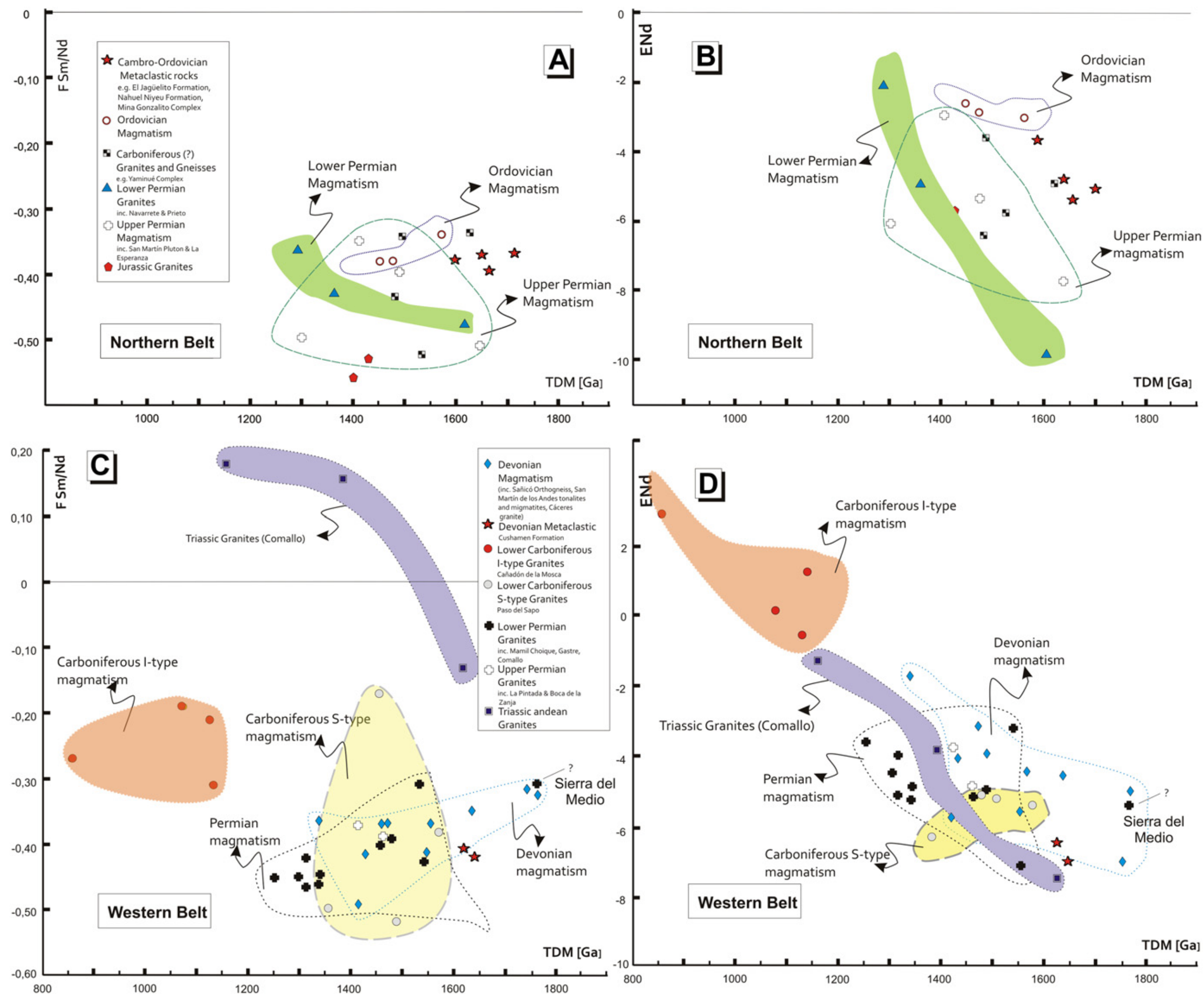

Fig. 5. (A) $f_{Sm/Nd}$ parameter vs. T_{DM} plot for the Paleozoic units of the Western belt NPM (B) $f_{Sm/Nd}$ parameter vs. T_{DM} plot for the Paleozoic units of the Northern belt NPM (C) Sr–Nd initial isotope composition plot for the Western Belt (D) and Northern Belt. Based on Table 2.

values of $f_{Sm/Nd}$ (−0.37 to −0.4) (Table 2). This late Paleoproterozoic bulk model age and associated parameters argue against juvenile supply in its consolidation as a rock. The ε_{Nd} value also implies that the sediments extracted from a ~1.7 Ga Paleoproterozoic crustal source. The other meaningful metasedimentary unit in the Sierra Grande area, the Mina Gonzalito gneiss (Table 2, Fig. 3), exhibits similar Sm–Nd isotope signatures (ε_{Nd} (t) −5; T_{DM} (Nd) 1.65 Ga) as the low-grade metasedimentary rocks derived from El Jagüelito and Nahuel Niyeu formations. However, it has a slightly older depositional age and therefore reinforces the evidence for reworking of Paleoproterozoic crustal material within the area.

Ordovician granitoids intruding the low grade metaclastic units (Fig. 3) can be found in northeastern North Patagonian Massif in two areas, west of Valcheta and Sierra Grande. Sm–Nd information is only available for Arroyo Salado, Playas Doradas and Sierra Grande granites (Fig. 2).

Younger Paleozoic magmatism is represented in the area by the Yaminué Complex and the Navarrete Plutonic Complex. The Yaminué Complex (Table 2) exhibits T_{DM} (Nd) values between 1.48 and 1.63 Ga, mean crustal f_{Sm-Nd} values of −0.34 to −0.53 and a range of ε_{Nd}(t) from −3.6 to −6.1. These values seem to typify different degrees of recycling in the bulk crustal segment as they all derive from a crustal source with slightly different T_{DM} (Nd). In general however, all cases show a main continental crustal recycling of Mesoproterozoic material as demonstrated by the crustal ε_{Nd}(t) and resulting T_{DM} (Nd).

Permian magmatism reveals a different situation within an episode of mixing of unequal parts of an old recycled crust, as demonstrated by the wide range in ε_{Nd}(t) and T_{DM} (Nd) ages between 1.3 and 1.65 Ga (Table 2). The calc-alkaline granodiorite of the Navarrete Plutonic Complex at Pto. Navarrete (Table 2) shows T_{DM} (Nd) ages of 1.3 Ga and relatively radiogenic ε_{Nd}(t) values (−2.08), suggesting a shift in the mixing ratio of the recycled bulk crustal material. The age of this bulk crustal source could be considered as younger than 1.6 Ga due to the recycling processes of magma during Ordovician times. High K-calc-alkaline series of the San Martin Granodiorite shows T_{DM} (Nd) ages of almost 1.5 Ga and ε_{Nd}(t) of −5.3, which could be explained as pure recycling of the bulk crust.

The most conspicuous extension of this Late Permian–Triassic magmatism is exposed in La Esperanza. The Early Permian granitoids of the Prieto and Donosa facies as well as the Late Permian rhyolithic domes of the Dos Lomas Complex and the Calvo Granite show a range of T_{DM} (Nd) from 1.30 to 1.64 Ga, $\varepsilon_{Nd}(t)$ values between −5 and −9 and normal to low $f_{Sm/Nd}$ values −0.4 to −0.5. These range of isotopic values for rocks of slightly different crystallization ages allow to infer that, Permian magmatism in La Esperanza may have involved an episode of dominant crustal recycling as it could be produced by a massive progressive melting of lower continental crust with little influence of juvenile material. A similar process might be identifiable in the highly fractionated Lower Jurassic Flores Granite and Las Grutas Granodiorite (Table 2), in the Valcheta area, which exhibits T_{DM} (Nd) ages of 1.4 Ga and $\varepsilon_{Nd}(t)$ values of −5.3.

5.2. Isotopic evolution of the Western Belt during the Paleozoic

The Colohuincul Complex has always been recognized as the oldest rocks on the western belt (see for instance Varela et al., 2005 and Pankhurst et al., 2006). The data for the Colohuincul Complex collected in the present study represents an inhomogeneous group of rocks such as sillimanite-biotite bearing gneisses, migmatites, orthogneisses, tonalites and metadioritic enclaves.

The metamorphic association primarily involves the orthogneisses of Sañicó and the enclaves within, the orthogneissic lenses of a medium metamorphic host rock near Laguna del Toro, the two-mica granodioritic gneiss of Sierra del Medio, and the migmatites and gneisses of San Martín de los Andes (Fig. 2). These rocks yielded T_{DM} (Nd) model ages that mostly range between 1.4 and 2.1 Ga. An isolated value of 2.1 Ga was obtained for a metadioritic enclave in an orthogneiss exposed near Sañicó and a 1.4 Ga value in a migmatite in San Martín de Los Andes. In the Sañicó-Comallo area (Fig. 2) the $f_{Sm/Nd}$ of the association show typical crustal values (−0.30 to −0.4), consistent with $\varepsilon_{Nd}(t)$ of −9 to −7 and a consistent mean −5 in the remnant ones.

Sm–Nd isotopic parameters from San Martín de los Andes Tonalite are slightly different: model ages indicate 1.4 Ga and the $\varepsilon_{Nd}(t)$ calculations yielded −3 to −4 mean values with a large range and an isolated $\varepsilon_{Nd}(t)$ value of −1.7 for a granite in the northeastern shore of the Lolog lake, near San Martín de Los Andes.

In the southern part of the Western Belt, near Río Chico town, the Devonian metasedimentary Cushamen Formation, shows T_{DM} (Nd) model ages around 1.6 Ga, compatible with the background bulk crustal age of 1.7–1.6 Ga as stated before in the north. The $\varepsilon_{Nd}(t)$ between −6.4 and −7 indicate recycling of old continental crust without juvenile additions.

The amphibolites and granodiorites of the Cañadón de la Mosca arc-related rocks, as referred by Pankhurst et al. (2006) and Ramos (2008), seem to typify a subduction-processed subcontinental lithosphere. This is evidenced by their positive to slightly negative $\varepsilon_{Nd}(t)$ values (−0.6 to +2.8), closer to the depleted mantle source, and lower $^{87}Sr/^{86}Sr$ initial ratios (Pankhurst et al., 2006). All samples show Neoproterozoic T_{DM} (Nd) model ages (0.8–1.1 Ga). The amphibolites show lower values than the tonalites at the same $f_{Sm/Nd}$, therefore they would not represent the pure source of this arc and would involve some kind of crustal contamination.

The Early Permian medium K-calc-alkaline igneous suites of the Sierra de Mamil Choique and Rio Chico area (López de Luchi and Cerredo, 2008) show T_{DM} (Nd) model ages between 1.25 and 1.34 Ga. The $\varepsilon_{Nd}(t)$ values for these rocks range from −3.2 to 5.2 with an almost invariable f_{Sm-Nd} (−0.45). Further south, Sm –Nd isotope results for the Sierra del Medio, granitoids indicate two different units (Table 2): a gneiss with a T_{DM} (Nd) of 1.76 Ga, which is similar to the T_{DM} (Nd) of the Cushamen Formation, and another sample with a younger T_{DM} (Nd) of 1.46 Ga, both ranging in $\varepsilon_{Nd}(t)$ from −5 to 5.5. In the Laguna del Toro area Devonian orthogneiss interlayered with the Cushamen Formation display T_{DM} (Nd) values of 1.76 Ga. This age is similar to the oldest data of Sierra del Medio and Cushamen Formation, whereas near Gastre two samples a biotite gneiss and a biotite granodiorite yielded slightly different parameters T_{DM} (Nd) 1.48 Ga, $\varepsilon_{Nd}(t)$: −5 and T_{DM} (Nd) 1.25 Ga, $\varepsilon_{Nd}(t)$: −3.6, respectively.

6. Discussion

Discussion of the data addresses the following topics. (1) Is the North Patagonian Massif basement a single autochthonous crustal block? (2) Can we correlate the different metamorphic events and magmatic pulses from eastern and western areas? (3) Is its isotope signature comparable to its neighbours', i.e. the Eastern Sierras Pampeanas (Pampia), Arequipa-Antofalla, Río de la Plata Craton?

6.1. Is the NPM basement a single autochthonous crustal block?

The oldest (meta-)sedimentary rocks in the massif, the fine to medium-grained metasediments from the early Cambrian (Nahuel Niyeu, El Jagüelito formations) and the Devonian?–Lower Carboniferous (Cushamen Formation) basins, in the northern and western borders of the massif respectively, show coherent average extraction ages in the Late Paleoproterozoic from its Paleoproterozoic sources (T_{DM} (Nd) between 1.6 and 1.8 Ga) similarly to the findings of Lucassen et al. (2004) for Late Paleozoic igneous and metamorphic rocks of the Andean Cordillera between 36° and 41°S.

Although the correlation of the older crustal segment identified in the Northern belt with the Devonian–Carboniferous metasediments and the Devonian orthogneisses of the Western belt only based on inheritance and age of sources is not reliable enough, the Nd parameters for these units indicate that they might have been formed by recycling of an equivalent crust of ca. 1.7 Ga. In agreement with that Lucassen et al. (2004) found single stage-T_{DM} (Nd) model ages between 1.6 and 2.1 Ga for this Paleozoic basement. Their data, as well as ours, confirm that the bulk crustal age at Early Paleozoic times would be 1.6–2.1 Ga. The limited available Sm–Nd isotope data for Devonian orthogneisses from Sañicó and from Sierra del Medio and southeast laguna del Toro indicate a similar average crustal age of ca. 1.7 Ga with $\varepsilon_{Nd}(t)$ of −5.

6.2. Correlation of different metamorphic and magmatic events from the eastern and western belts

6.2.1. Timing of metamorphism

In the northeastern area of the North Patagonian Massif, sedimentation is younger than 515 Ma (Pankhurst et al., 2006). The metamorphic event affecting these sedimentary units which was dated at 478 Ma in the Mina Gonzalito Complex (Pankhurst et al., 2006) agrees with sharp contacts against El Jagüelito Formation – and enclaves of it in the (476 Ma) – Ordovician Arroyo Salado pluton.

For the Western Belt Pankhurst et al. (2006) proposed a Carboniferous age of metamorphism based on the inheritance zircon pattern for El Maitén gneiss and related this metamorphism to the docking of the Deseado Massif terrane. A reinterpretation of the detrital zircon pattern of the El Maitén gneiss and Cushamen Formation (Pankhurst et al., 2006; Hervé et al., 2005) indicates well defined peaks at 370–380 Ma and 425–440 Ma. The 425–440 Ma peak explanation is still obscure, mostly because there is no clear isotope dating that yields these crystallization ages. Ages of 419 ± 27 Ma in a tonalite near the city of San Martin de los Andes and the 428 ± 25 Ma in Sañicó obtained by conventional U–Pb in zircon by Varela et al. (2005), have proven to be at the moment, the closest suppliers for these zircons. The 400 Ma zircon supply is coincident with the well stated crystallization ages of the ∼395 Ma in a tonalitic gneiss of the Colohuincul Complex (Godoy et al., 2008) and in a tonalite in the Cerro Curruhuinca (Varela et al., 2005).

A 370–380 Ma metamorphic age was also calculated near Collón Cura by the crystallization age of a titanite (close to the metamorphic peak) of Lucassen et al. (2004). In the area of Río Chico (Fig. 4), timing of metamorphism is constrained as pre-dating the emplacement (Cerredo et al., 2000) of the 295 Ma Tunnel Tonalites (Pankhurst et al., 2006) or as late Devonian–Early Carboniferous (Ostera et al., 2001). This Devonian metamorphic event could be extended up to Gastre, in the Laguna del Toro area (Fig. 2) by considering the U–Pb SHRIMP zircon age of 371 ± 3 Ma obtained by Pankhurst et al. (2006) in an orthogneiss interlayered with the Cushamen Formation.

The age of metamorphism was interpreted to be ca.330 Ma age, but that age could result from the opening of the isotopic system during a juvenile magmatic addition associated with an extensional regime as suggested by previous studies on the metamorphic assemblages of the Cushamen Formation, which show P–T decompression paths related to an extensional regime postdating the peak metamorphic conditions (López de Luchi and Cerredo, 2008).

6.2.2. Magmatic belts

An Ordovician tectono-magmatic episode has been widely recognized in the northeastern corner of the North Patagonian Massif as represented by calcalkaline I-type granitoids such as Valcheta pluton and Sierra Grande pluton among others (Caminos, 2001; Tohver et al., 2008; Gozálvez, 2009). Field and petrographic evidence of magmatic hybridization (Lopez de Luchi et al., 2010; Rapalini et al., 2010) together with younger than the value for the bulk Patagonian crust T_{DM} model ages together with more positive $\varepsilon_{Nd}(t)$, would fit the mixing hypothesis.

The oldest recognized basement rocks in the western belt are Silurian to Devonian in the area of San Martín de los Andes and Sañicó or Devonian southeast of Laguna del Toro and probably in the Sierra del Medio. While this magmatic and metamorphic episode took place in the Western belt, deposition of the Sierra Grande Formation sediments occurred in the northeastern of the North Patagonian Massif. These marine sediments do not show evidence of metamorphism or Pre-Permian tilting and demonstrate that processes in both margins are independent.

During Carboniferous times, after the deposition of Sierra Grande Formation in the Northern belt, the Yaminué Complex was emplaced. Although age constrains for this complex are somewhat dubious, Sm–Nd isotope parameters argue for dominant crustal recycling as a source for these deformed mostly syn-tectonic (Chernicoff and Caminos, 1996; Lopez de Luchi et al., 2010) granitoids.

Carboniferous magmatism in the western belt shows two separate magmatic events. A basic-mesosilicic association, which taps a ca 1.1 Ga source and another that exhibits a less radiogenic signature and T_{DM} (Nd) of ca 1.4–1.5 Ga. The first is considered as related to an active arc whereas the latter, at least in part, is related to a collisional event. (Pankhurst et al., 2006).

The T_{DM} (Nd) interval 1.4–1.5 Ga is characteristic of the Devonian magmatism in the San Martín de los Andes area. As this age interval in the Carboniferous granitoids is associated with both more negative f and epsilon parameters recycling of a bulk segment of the crust generated during the Devonian might be suggested. The presence of this crust is further supported by the inheritance pattern in the zircon of Cushamen Formation.

This evidence would lead to consider that the Devonian arc magmatism could have extended down to the southwestern sector of the North Patagonian Massif. If the western margin of the NPM were an active margin during Devonian times, it might have been closed before the Carboniferous as indicated by the ca. 360–380 Ma metamorphic age of Cushamen Formation and associated rocks (Ostera et al., 2001; Lucassen et al., 2004). In this scenario rocks of Cordón del Serrucho are compatible with emplacement during an extensional tectonic regime, as suggested by post-peak metamorphism P–T decompression paths observed in Cushamen Formation (López de Luchi and Cerredo, 2008).

Late Carboniferous–Permian magmatism can be traced along the northern and western border of the North Patagonian Massif (Fig. 2). Subduction and collision followed by post-collisional magmatism (Llambías et al., 1984; Rapela and Caminos, 1987) was originally proposed for the Late Paleozoic evolution of the NE border of Patagonia mostly based on geochemical data. Pankhurst et al. (2006) proposed that the widespread Permo-Triassic magmatism in the North Patagonian Massif was the result of a slab break off after the Carboniferous collision between NPM and DeM. Recently López de Luchi and Cerredo (2008) argued for a post-collisional melting event as the source for the Permian granitoids of the Sierra de Mamil Choique (Fig. 4), which either show features of hybridization i.e interaction with more mafic components or are homogenous crustal granites. On the other hand, Llambías et al. (2002) supported the idea of a NW–SE distribution of Permian magmatism along the NE border of the NPM, San Rafael Block and Frontal Cordillera, parallel to the Gondwanides arc.

Late Carboniferous-Permian granitoids cover the T_{DM} (Nd) interval from 1.25 to 1.64 Ga in which three main cycles can be distinguished.

(i) An older cycle that includes deformed granitoids that crystallized prior to 295 Ma and exhibits T_{DM} (Nd) around 1.5 Ga.
(ii) A second cycle represented in the hybrid magmatic units crystallized post 295 Ma, which displays T_{DM} (Nd) between 1.3 and 1.4 Ga.
(iii) A younger cycle (around 260 Ma) in which magmatism would result from pure recycling of a 1.5 Ga or slightly older continental crust.

6.2.2.1. Previous to 295 Ma – turning point. After the deposition of Sierra Grande Formation in the Northern belt, the Yaminué Complex was emplaced. Although age constrains for the latter unit are somewhat dubious, Sm–Nd isotope parameters argued for dominant crustal recycling (T_{DM}(Nd) of 1.5 Ga) as a source for these deformed mostly syn-tectonic (Chernicoff and Caminos, 1996; Lopez de Luchi et al., 2010) granitoids. Yaminué Complex comprises not only calc-alcaline orthogneisses, but also syncollisional leucogranitoids (Cabeza de Vaca, see Lopez de Luchi et al., 2010 for more details) and it is overlain by the undeformed Navarrete Plutonic Complex (281 Ma). T_{DM}(Nd) of around 1.5 Ga are also found in the western belt, in Sierra del Medio, with a two-mica gneiss giving an age 1.45 Ga. The same is true for the area of Laguna del Toro, (Fig. 2) where a similar T_{DM}(Nd) was assigned to a granite gneiss, similar to a ca.1.5 Ga obtained for a foliated tonalite and a 1.4 Ga for La Pintada granite, both located in the Sierra de Mamil Choique. Farther north, in the area east of Comallo an equivalent T_{DM}(Nd) was reported for a foliated tonalite with a cooling age of 281 ± 17 Ma by Varela et al. (2005). All these rocks are pervasively deformed and their Sm–Nd isotope signature could be comparable with some of rocks of the Paso del Sapo and Pichiñanes area. The Sm–Nd isotope characteristics (Table 2) and lithologies suggest that the genesis of these granitoids may have involved a crustal segment similar to that generated in association with the Devonian magmatism. Therefore it could be speculated that these rocks are older than the 295 Ma Tunnel Tonalite cropping out near Rio Chico.

6.2.2.2. Post 295 Ma – turning point. The mafic facies of the Permian magmatism could be traced in both belts, from the NW corner near the city of San Martín de los Andes up to Valcheta town and the southeastern locality of Gastre (Fig. 2). Dalla Salda et al. (1991) and Varela et al. (1992) had already described tonalitic facies in the Piedra del Aguila and Chasicó-Mencué areas. Descriptions and chemistry of these units strongly resemble the hybridized 273 Ma Prieto Granodiorite (T_{DM} 1.36 Ga) and some facies of the 282 Ma Navarrete Plutonic Complex (T_{DM} 1.29 Ga). On the other hand, Varela et al. (1994) provided a very well fitted Rb–Sr isochron (285 ± 5 Ma) for diorites and biotite rich-granodiorites with xenoliths assigned to the Huechulafquen Formation, north of Junín de los Andes. Along the southwestern border of the massif reworking of the mafic lower crust is indicated by the combination of 1.3 Ga T_{DM}(Nd) model ages and negative crustal epsilon values in the Sierra de Mamil Choique (López de Luchi and Cerredo, 2008). All these rocks exhibit hybridization features like amphibole clots with sphene as a common accessory mineral together with variable amounts of magnetite and apatite and microgranular enclaves.

Therefore, if Sm–Nd isotope parameters are taken together, the Late Paleozoic magmatism in the northern and western belt might have recorded a change of source in the mixing process around 295 Ma from a source with an average crustal residence age around 1.5 Ga to a dominantly mafic source yielding slightly younger T_{DM}(Nd) model ages of 1.3–1.4 Ga.

The thermal event that may lead to the production of these massive hybrid magmas may respond to a step by step melting of different levels of the continental crustal with a lower crustal mafic pole (ca. 260 Ma).

6.2.2.3. 260 Ma – widespread magmatism. The upper crustal undeformed Late Permian to Triassic granitoids, which are mostly located in the Northern belt, recorded the recycling of a source with a non-radiogenic older average crustal residence age of 1.6 Ga based on data from Donosa granite, Calvo granite, Collinao Dacite and the San Martín pluton.

Therefore it could be proposed that at ca. 260 Ma the amount of involved juvenile material (either metasomatised levels of a mafic lower crust or subcontinental mantle) is decreasing . These inferences on the Permian magmatism might support the hypothesis of slab-break off (Pankhurst et al., 2006) perhaps linked to a collision on the northeastern margin of the North Patagonian Massif (Rapalini et al., 2010) with which in turn the 295 Ma change from a 1.5–1.4 Ga source to ca. 1.3 Ga source could be related .

Younger units, like the Jurassic Flores Granite or El Sótano Granodiorite (Sato et al., 2004), have a completely different signature than their western counterparts along the southern Andes, where Lucassen et al. (2004) pointed out that the Mesozoic granites clearly split from the Paleozoic trend. The low $f_{Sm/Nd}$ and $\varepsilon_{Nd}(t)$ signatures of the Flores granite suggest a continuum of the recycling processes within the upper crust.

6.2.3. Relationship with the neighbouring crustal units

Relationships of the North Patagonian Massif with its neighbouring crustal domains might be established from their isotopic and geologic features. Several South American crustal blocks or terranes (Fig. 1) were analysed: the Deseado Massif, the Río de la Plata Craton, the Arequipa-Antofalla composite block, the Eastern Puna, the Western Puna, Maz terrane (Casquet et al., 2008), the Eastern Sierras Pampeanas and the Cuyania Terrane.

For this comparison we used the compilation previously prepared by Steenken et al. (2004), and add new and recalculated data for Late Neoproterozoic to Paleozoic metaclastic rocks of different landmasses from Loewy et al. (2003, 2004), Bock et al. (2000), Lucassen et al. (2000), Drobe et al. (2009), Casquet et al. (2008), Rapela et al. (1998), Porcher et al. (2004), Cingolani et al. (2003) and Augustsson and Bahlburg (2003, 2008).

Pankhurst et al. (2006) proposed that southern Patagonia (the Deseado Massif) collided with the North Patagonian Massif in Carboniferous times in order to explain the successive episodes of Late Paleozoic granitic magmatism in central Patagonia. However, there is yet no agreement on whether this block is allochthonous or parauthochthonous. Comparison of Nd isotope data for contemporary metaclastic units of the North Patagonian Massif with the Cambro-Ordovician La Golondrina and Dos Hermanos metaclastic units (Pankhurst et al., 2003) and the Devonian–Carboniferous turbidites of Bahía La Lancha and Cochrane Formations (Augustsson and Bahlburg, 2003, 2008) shows significant differences in both f_{Sm-Nd} vs. T_{DM} and $\varepsilon_{Nd}(t)$ vs. T_{DM} diagrams (Fig. 6a and b). Although data are scarce for both massifs, the Deseado Massif has a mean crustal residence age younger than ~1.7 Ga, whereas the NPM yielded T_{DM}(Nd) ages between 1.6 and 1.7 Ga. Moreover, the f_{Sm-Nd} and $\varepsilon_{Nd}(t)$ parameters are considerably more positive in the Deseado Massif Cambro-Ordovician rocks than in those of the North Patagonian Massif, which suggest a more-depleted source. On the other hand, Devonian–Carboniferous data from the metaturbidites of the Bahía La Lancha, Río Lácteo and Cochrane Formations exhibits a wider range of model ages as well as $\varepsilon_{Nd}(t)$ values than those from equivalent units in the North Patagonian

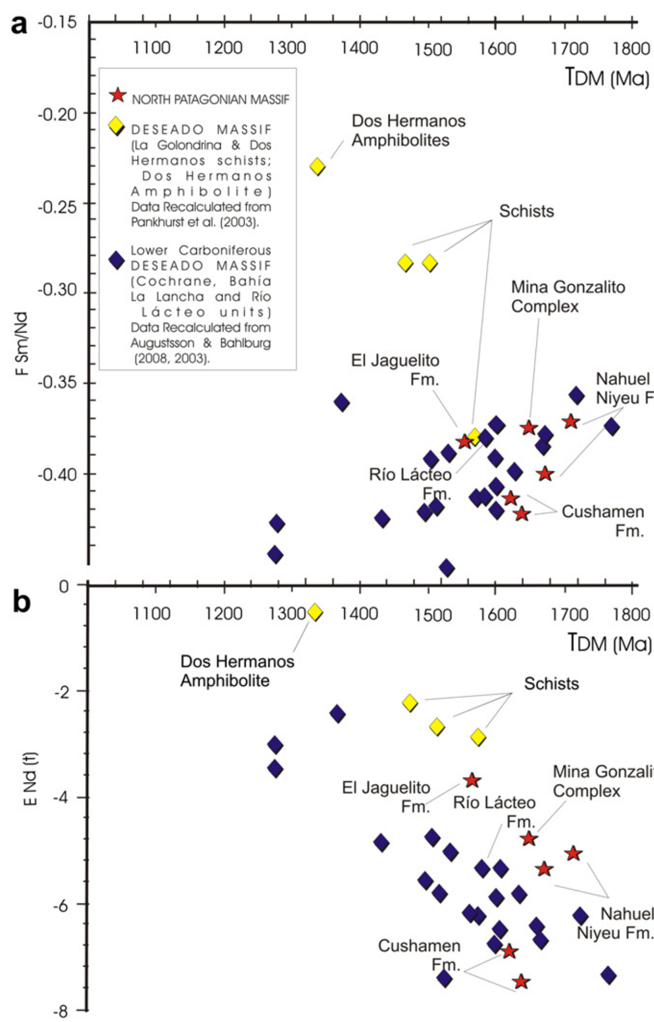

Fig. 6. (a) $f_{Sm/Nd}$ parameter vs. T_{DM} (Nd) plot for the Paleozoic metaclastic rocks of the NPM and Deseado Massif (b) Sr–Nd initial isotope composition plot. Data for the Deseado Massif have been recalculated from Augustsson and Bahlburg (2003) for Bahía La Lancha and Cochrane units and Pankhurst et al. (2003) for Dos Hermanos and La Golondrina schist.

Massif that may imply as proposed by Augustsson and Bahlburg (2008), a multisource supply of felsic and recycled crust, partially in agreement with the Nd isotope parameters values of NPM's Cushamen Formation. Recently Schilling et al. (2008) using Re–Os isotopes proposed that the Deseado Massif continental block is older (1.3–2.1 Ga) than the NPM. Evidence so far is not enough to provide a unique interpretation because these two crustal blocks could either represent different crustal domains, or have undergone different processes of recycling that have been more effective during the Mesoproterozoic. However Sm–Nd isotope signatures suggest that the Early Paleozoic metaclastic rocks from each massif would have sources of different average crustal residence time whereas younger metaclastic and sedimentary rocks (i.e Cushamen Formation in North Patagonian Massif and Bahía la Lancha, Río Lácteo, and Cochrane formations in Deseado Massif) share comparable Nd parameters (Fig. 6).

The 1.6–1.8 Ga – Late Paleoproterozoic – T_{DM}(Nd) ages of the North Patagonian Massif clearly contrast with those from the Rio de la Plata craton (see Steenken et al., 2004 for comparison), suggesting a significantly different Proterozoic crustal evolution (Fig. 7A) Recently, Casquet et al. (2008) splitted a Mesoproterozoic crustal domain – the Maz terrane – from the Western Sierras Pampeanas and proposed its crustal affinity with the northern and central domains of the Arequipa-Antofalla Block. The recalculated Sm–Nd isotope data for the Maz terrane are shown in Fig. 7A.

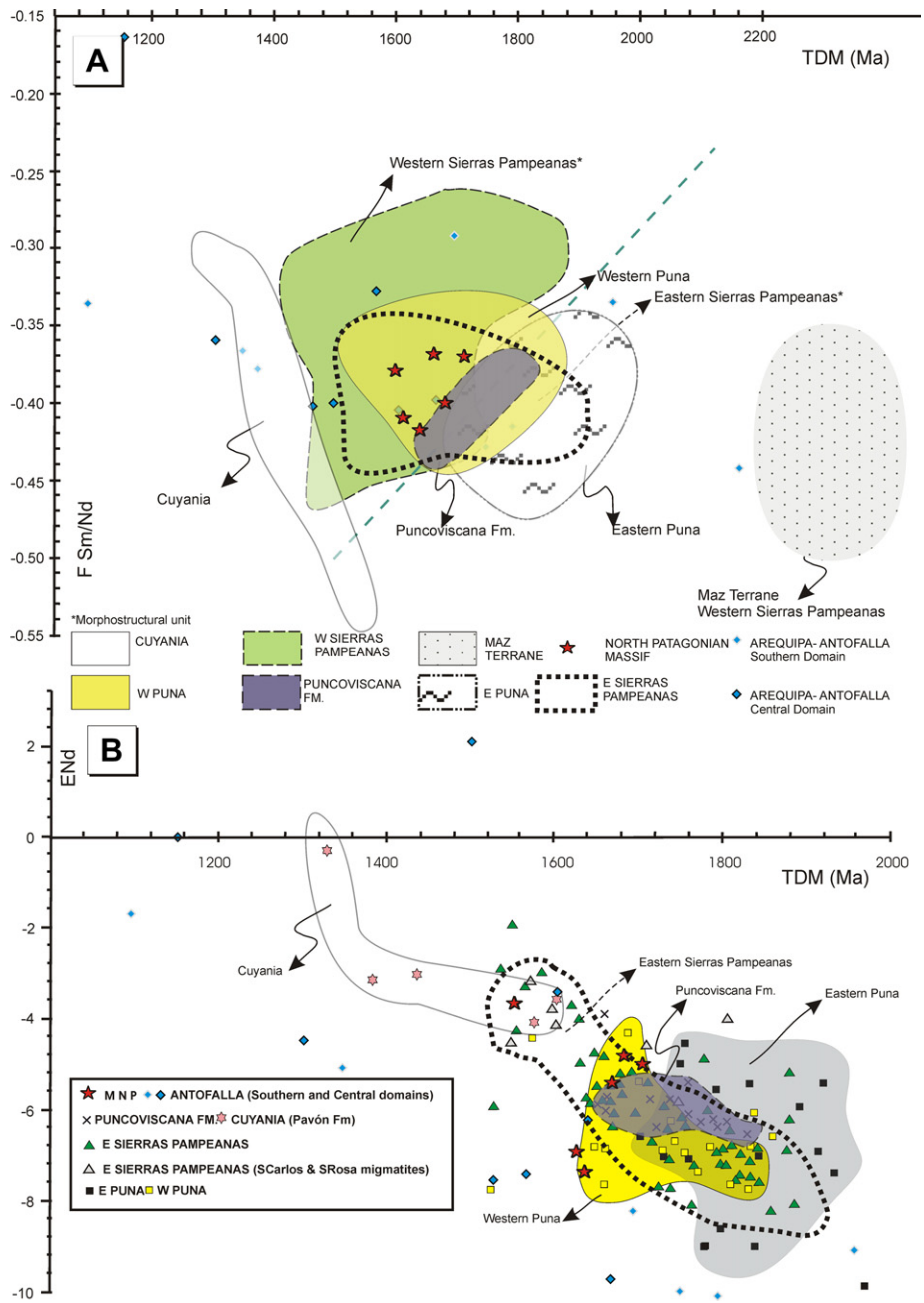

Fig. 7. (A) $f_{Sm/Nd}$ parameter vs. T_{DM} plot for the Paleozoic metaclastic rocks of the NPM and the neighbor terranes (B) Sr–Nd initial isotope composition plot. Data from Pavón Formation (Cingolani et al., 2003); Sierras Pampeanas (Rapela et al., 1998; Porcher et al., 2004; Drobe et al., 2009); Puncoviscana Formation (Bock et al., 2000); Eastern Puna; Western Puna and Southern and Central block of the Arequipa-Antofalla craton (Bock et al., 2000; Lucassen et al., 2000; Loewy et al., 2004) and Maz terrane (Casquet et al., 2008).

Model ages for the North Patagonian Massif are similar to those from the Sierras Pampeanas (Steenken et al., 2004; Drobe et al., 2009; Casquet et al., 2008; Porcher et al., 2004), Western Puna, and the Central and Southern domains of the Arequipa-Antofalla block (Loewy et al., 2004) suggesting that the North Patagonian Massif might have a Proterozoic crustal connection with them. Data from the central and southern domains of the Arequipa-Antofalla composite block (Lucassen et al., 2000; Loewy et al., 2004) belonging to the Quebrada Choja and Quebrada Arcas in northern Chile (southern Central Domain, Lucassen et al., 2000 and Loewy et al., 2004) and the Limón Verde and Centenario Formations (Southern Domain, Lucassen et al., 2000) (Fig. 7A and B) is scarce. In this scenario (Fig. 7A and B), the age ranges that might be defined for both domains of the Arequipa-Antofalla block overlap and are roughly consistent with the North Patagonian Massif age range.

Puna has been subdivided into a western and an eastern sector, excluding the Puncoviscana Formation. Data used for the Western Puna includes the Ordovician volcanosedimentary and turbiditic successions, while data from the sedimentary Mesón Group and metasedimentary deposits in the Cerro Queta, Río Taiques, Sierra de Cobres and Cordón de Escaya (Bock et al., 2000) were taken for the Eastern Puna. These two groups only partially overlap in their $f_{Sm/Nd}$ and $\varepsilon_{Nd}(t)$ values with the T_{DM}(Nd), thus clearly overlapping with the Puncoviscana Formation field (Fig. 7B).

Data for the metaclastic units of Eastern Sierras Pampeanas, mostly grouped in different metamorphic complexes are distinguished on the basis of the Sm–Nd systematics. Since there is no consensus in the recent literature on how these complexes and metasediments are related they were considered as a single unit for regional comparison (Fig. 7A and B).

The North Patagonian Massif metasediment data plots in the area of overlap of the Eastern Sierras Pampeanas, Western Puna and Puncoviscana Formation ranges. Inside the Eastern Sierras Pampeanas domain, the Metamorphic Complexes (Nogolí, Pringles and Conlara) plus the migmatites of the San Carlos Massif (Fig. 7A and B) clearly detach from the metaclastics of the San Luis Formation and Sierra de Chepes (Drobe et al., 2009). Although little data is available from the North Patagonian Massif, the Sm–Nd isotope results are similar to the pre-Famatinian metamorphic rocks of the Eastern Sierras Pampeanas.

The relationship between the Ordovician magmatism and metamorphism in the basement of San Luis, La Pampa and the northeastern part of the North Patagonian Massif could be explained by crustal continuity of the Pampia terrane into the NPM since at least the Early Cambrian (Rapalini et al., 2010, and references therein). The similarity of the spectra of detrital zircon data available from the Lower Paleozoic metasedimentary units of the North Patagonian Massif (Pankhurst et al., 2006) and others from the Eastern Sierras Pampeanas (Cantera Green, Chernicoff et al., 2007, and Pringles Metamorphic Complex, Steenken et al., 2004) is evident. The low to medium grade metasedimentary rocks share not only a small Grenvillian peak (~1.0 Ga) but also a minor 2.0 Ga peak. Moreover, they all exhibit a peak around the 510–520 Ma, coincident with the provenance pattern found in other post-Pampean basins (Fig. 8).

Inheritance patterns from the Silurian–Devonian sediments of the Sierra Grande Formation (Uriz et al., 2008) exhibit supplies

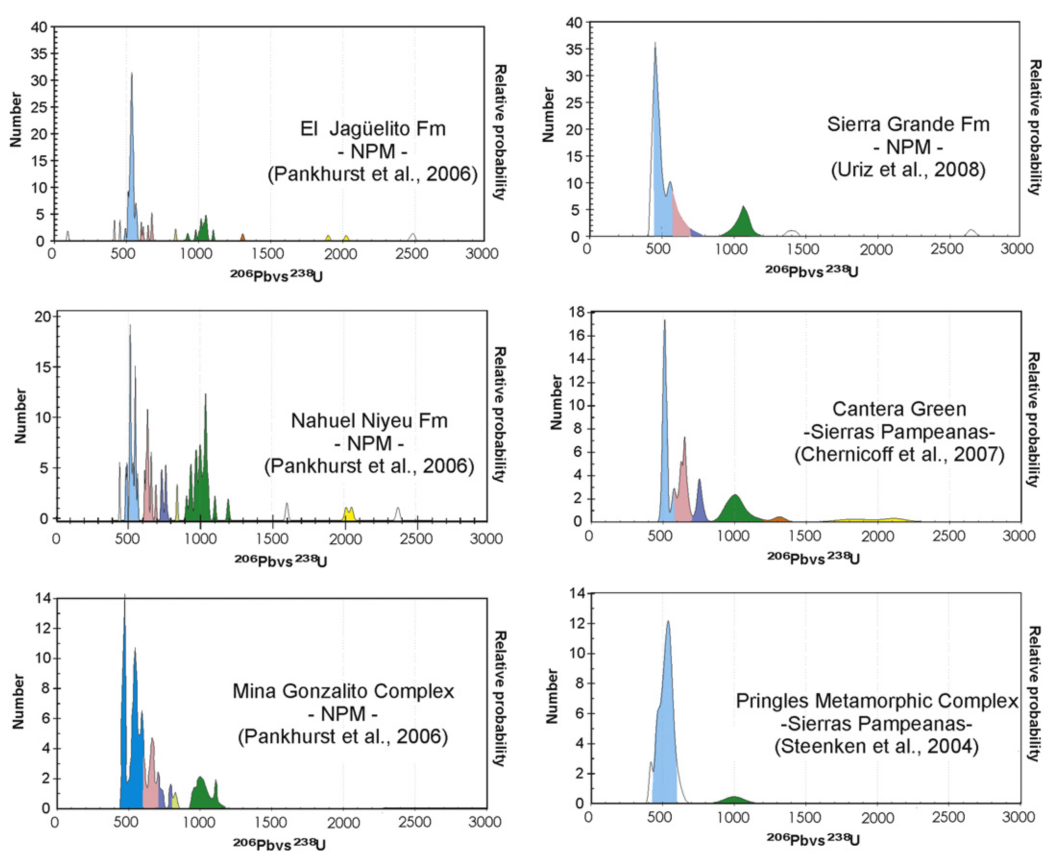

Fig. 8. U–Pb provenance age patterns for metasedimentary samples from El Jagüelito and Nahuel Niyeu Formations; Mina Gonzalito Complex from the North Patagonian Massif; Cantera Green Formation and Pringles Metamorphic Complex from Eastern Sierras Pampeanas. NPM - North Patagonian Massif-Data from Devonian-Sierra Grande Formation is also included. Data taken from Pankhurst et al. (2006), Steenken et al. (2006), Chernicoff et al. (2007) and Uriz et al. (2008).

from rocks of 480 Ma (Famatinian peak), 523 Ma (Pampean peak), 608 Ma (Brazilian peak) and ~1000 Ma (Grenville peak). The last three peaks also appear in the zircons of the Cambrian (?) sediments of Nahuel Niyeu, El Jagüelito formation, Mamil Choique Granitoids (Fig. 8) reinforcing the idea of such crustal relationships.

7. Conclusions

7.1. Crustal structure and processes

U/Pb ages of the oldest rocks exposed in the northeastern corner of the North Patagonian Massif (Cambrian to Ordovician) are significantly different with respect to those exposed in the western sector having maximun reliable Devonian ages. However Sm–Nd isotope characteristics delineate a basement domain, apparently formed during the Paleoproterozoic between the 2.1 and 1.7 Ga, and then subsequently recycled. The first stage of crustal growth is shown by the Ordovician granites of the Valcheta and Sierra Grande areas with mixed sources appear to be fairly depleted-in comparison to its older metamorphic host and younger neighbouring intrusions. In the Western Belt, inhomogeneous crustal mixing is suggested by $\varepsilon_{Nd}(t)$ values and field evidence, hence for Devonian times the main crustal-forming mechanism was recycling of the bulk crust. The Carboniferous to Permian intrusions in the northeastern and southwestern regions of the North Patagonian Massif were produced from an already recycled old Mesoproterozoic crust partially contaminated with a low proportion of a lower crustal mafic source.

The Sm–Nd isotope data allows distinguishing a step by step melting of different levels of the continental crust during the succesive evolution of late Paleozoic magmatism. Between 330 and 295 Ma magmatism was likely the product of a crustal source with an average residence age of 1.5 Ga. Isotope, petrographic and field evidence indicate that the widespread magmatism represented by the 295–260 Ma granitoids (Tunnel Tonalite, Mamil Choique granitoids, Prieto Granodiorite and Navarrete Complex) involved the fusion of a lower crustal mafic source, and continued with the production of massive shallower-acid plutono volcanic complexes, which might be entirely attributed to the recycling of an upper crustal segment of the Proterozoic continental basement.

7.2. Neighbouring terranes

The regional compilation and recalculation of T_{DM}(Nd) ages for the Early Cambrian to Devonian metasedimentary units of the North Patagonian Massif indicate a late Paleoproterozoic crustal signature, which is similar to those found in the Eastern Sierras Pampeanas (or Pampia terrane) and the southern and central domains of the Arequipa-Antofalla block. On the other hand, these model ages suggest significantly different crustal sources for the North Patagonian Massif in comparison to the Maz terrane and the allocthonous Cuyania terrane. Crustal continuity with the Paleoproterozoic–Neoarchean Río de la Plata craton, the oldest crustal unit of the region, is not supported, suggesting lack of continuity of both crustal blocks in Proterozoic times.

Similar detrital zircon age patterns between Early Paleozoic (meta)-sedimentary rocks from the northeastern North Patagonian Massif (Valcheta area) and those from the Eastern Sierras Pampeanas, and the apparent continuation of the Early Ordovician Famatinian magmatic arc into Patagonia might suggest crustal continuity between Pampia and the northeastern sector of the North Patagonian Massif by the Early Paleozoic. Nevertheless, petrological and isotopic signatures of the Early Ordovician granitoids in the Sierra Grande area show some differences with respect to those located north of Patagonia whose meaning is yet uncertain.

7.3. Final considerations

In this study we carried out a comprehensive review of chronological, petrographic and isotopic data of Paleozoic metasedimentary and magmatic rocks exposed in the North Patagonian Massif. In summary, we interpret that the North Patagonian Massif constitutes a crustal block that has been repeatedly affected by major tectonic events during its Neoproterozoic and Paleozoic history. Through massive recycling of different segments within the North Patagonian Massif two partially different evolutionary pathways along its northeastern and western margins developed. According to the cited evidence and our own analysis, there might have been a crustal continuity between the northeastern (Valcheta area) North Patagonian Massif, the Eastern Sierras Pampeanas and the southern and central domains of the Arequipa-Antofalla block. The absence of Early Palezoic rocks in the southern and western part of the NPM precludes the possibility to extend this hyphotesis to the western belt as well.

The convergence and possible collision of the Deseado Massif (plus the Antarctic Peninsula or other minor terrane?) might have caused Devonian (380–360 Ma) metamorphism and deformation. Devonian metamorphic ages on the western belt might be coincident to those proposed by Willner et al. (2008) for the collision of the Chilenia terrane with Gondwana.

In the southwestern area, a mixed magmatic source could be responsible for the ca. 330 Ma magmatism. The Permian sources that are dominated by 295 Ma intrusion ages exhibit younger T_{DM} around 1.3 Ga suggesting a higher input of mafic/more juvenile material into the mixing budget with bulk crust. Vigorous melting and rehomogenization of the lower (295 Ma) and upper crust (post 260 Ma) respectively, appear to have succeded at the turn of the Paleozoic. All this evidence suggests that at least the northeastern sector of the North Patagonian Massif is not allochthonous to Gondwana. Widely discussed evidence of a Late Paleozoic frontal collision with the southwestern margin of Gondwana (Ramos, 1984, 2008; von Gosen, 2003; Lopez de Luchi et al., 2010, etc) can be reconciled in a para-autochthonous model that includes a rifting event from a similar or neighbouring position to its post-collision location. The possibility of a Mid-Paleozoic small ocean basin between the North Patagonian Massif and Gondwana is permissible by the available paleomagnetic data (Rapalini, 2005). This plate tectonic history of the Pacific margin of west Gondwana is related to the evolution of the Terra Australis orogen (Cawood, 2005), controlled by absolute displacements of the Gondwana supercontinent and guided by successive plate reorganization. Possible Proterozoic or Early Paleozoic connections of the North Patagonian Massif with the Kalahari craton or the western Antartic blocks and Chilenia terrane should be investigated.

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